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DYNAMIC SYSTEM RENEWAL PLANNING MODEL

by

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September 1989

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Dynamic System Renewal Planning Model

by

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This thesis proposes a framework by which optimal system renewal decisions may be made in a consistent and timely manner within the military, under realistic conditions of changing environments. A unique network representation of the system renewal process was used to develop a prototype version of the analytical core model. Its plausibility and usefulness was demonstrated by a series of case studies. The case studies also show how pertinent staff forecasts can be organised and integrated to provide decision makers with a broad, consistent, long-term perspective of the issues relevant to system renewal planning. They are presented with a graphic picture of the entire solution space as structured by the scenarios considered. Various solutions are suggested for each scenario and their robustness may be tested by thoroughly exercising the model for a wide range of scenarios. Prediction of what and when renewals are likely to be and estimation of the associated cost and effectiveness allow anticipatory long-term plans to be formulated. The thesis also suggests how bulk versus phased procurement decisions and force level and mix issues could be analysed using the model.

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I. INTRODUCTION

A. INTRODUCTION

Military forces continually undergo change as obsolete or uneconomical assets are retired, new weapons are introduced and existing ones modified or upgraded. This process of system renewal is affected by a myriad of economic, technological and politico-military considerations. Changes in enemy capabilities or doctrine, for instance, may render certain systems less effective or even obsolete. New technology may offer opportunities to improve present capabilities. Most of the available open literature, analyses and models for system renewal are either one-dimensional, too general, or too commercially oriented to be useful to military planners. There is a need to synthesize a coherent, balanced view relevant to military planners to provide comprehensive policy guidance on upgrading, replacement and related matters.

B. PROBLEM

The system renewal planning problem is encountered prior to the last milestone of the defence acquisition cycle. It is basically one of being able to evaluate and decide in a timely and rational manner, under conditions of changing technological, economic and politico-military environments, both the following:

1. When will a defence asset, in its present form, become obsolete or no longer cost-effective to retain (relative to existing or emerging alternatives)?

2. What should then be done? What are the alternatives and which one should be chosen?

C. DEFINITION

System renewal encompasses all changes made to maintain or improve the cost-effectiveness of the present defence system. It includes the acquisition of new capabilities, retirement from service of obsolete ones, relegation to reserves of surplus capabilities and conversion of systems to new roles. This view streamlines the treatment of changes to the status quo and involves a higher level of system representation. It allows us to consider complex changes, such as when a new support ship displaces a couple of smaller ones, one of which is preserved for the boneyard and the other converted to a hospital ship.

D. PURPOSE

The purpose of this thesis is to develop a rational and consistent decision model for system renewal planning that is relevant and useful to military planners. Various issues pertinent to system renewal are integrated into a common analytical framework to make for a more comprehensive and better formalised concept of obsolescence in military systems.

This work is intended as a background study for later development of a comprehensive policy to complement life-cycle management initiatives in the Singapore Ministry of Defence. It serves as a rudimentary framework that can be expanded later for actual use.

E. IMPETUS

The choice of this research topic was motivated by the following:

- Singapore's defence buildup has been underway for two decades and already system renewal decisions are due for some of the aging systems that were acquired initially. A framework that facilitates taking the long-term perspective

in system renewal planning will help ensure that such optimal decisions are made in a systematic and timely manner. As the assets involved are considerable, improvements in system renewal planning is of significant importance.

- Milestone 5 (upgrading/replacement) was introduced in U.S. DoD Instruction 5000.2 in September 1987. No clear guidance has been provided on the approaches to be adopted for this new milestone.

- Available literature generally either deals with replacements aimed at preempting failure (preventive maintenance) or reduces the problem to a purely economic one (commercial approach). There is a dearth of literature of relevance to military system renewal planning.

F. SCOPE

Replacement policies concerning routine preventive maintenance are not examined in this thesis. The scope is limited to major systems or forces for which the considerable effort involved in identifying, tracking and analysing capability requirements, costs and measures of effectiveness (MOEs) are justifiable. At the heart of the framework to be presented is an analytical model, the workings of which will be illustrated under various assumptions based on a hypothetical weapon system. Attention is focused on single mission systems in changing environments. The treatment of threat evolution, force level planning and higher level optimisation are briefly discussed. Simple sensitivity analysis is illustrated but full and proper stochastic modelling and risk analysis lie outside the scope of this thesis.

II. ISSUES AND LITERATURE SURVEY

Systems are renewed as they become obsolete. Why? When is a system considered obsolete? What are the issues involved in planning for system renewal? These are the larger questions addressed in this chapter. We begin by explaining obsolescence and its consequences. Next, for a broad overview of the system renewal problem, various issues pertaining to the selection and scheduling of alternatives are discussed. The chapter ends with a survey of some of the research that have been carried out on system renewal.

A. OBSOLESCENCE

Obsolescence may be categorised as follows:

- *Economic:* A system is considered economically obsolete when it becomes less cost-effective than available alternatives because of cost escalation attributed to physical deterioration, scarcity of spares, inflation, etc. An old truck that breaks down often, guzzles fuel that has become expensive, or has little spares support is economically obsolete.

- *Technological:* This form of obsolescence occurs when innovation makes available a new, more cost-effective alternative to an incumbent system. Fighter planes with propellers, for example, became technologically obsolete when jet-propelled ones became available.

- *Operational:* Operational obsolescence arises when a system fails to meet its requirements because of deterioration in performance, enemy counter-measures or shifts in own strategic/tactical doctrine. Immobile defence systems, for

instance, may become obsolete if it is known that they can be effectively engaged or bypassed by the enemy, or if strategic emphasis shifts from attrition to maneuver warfare.

Obsolescence may be a compound effect of the above. A gun that is no longer accurate may also be uneconomical to maintain.

The continued operation of an obsolete system is always a waste of money, but technological and operational obsolescence may have more serious consequences. Failure to exploit technological opportunities or remedy operational deficiencies may lead to military disasters. Technology is not exploited merely by keeping pace with research as was shown by the French experience in 1939. The French Army then had for some time developed prototypes of aircraft, armor and antitank weapons superior to those of the German Army. Their wait for still better ones to come along before introducing them into the inventory was a reason for their unpreparedness [*Possony and* Pournelle, 1970]. The Polish Army's fatal cling to cavalry is a clear lesson in the consequence of operational obsolescence.

Not all obsolescence is bad. The term "built-in obsolescence" is sometimes used for the practice of deliberately designing machines that deteriorate rapidly after a given life; the user being compensated for this by a lower purchase price. This can be seen, for example, in commercial batteries with different lives.

B. STRATEGIC ISSUES

Defence forces exist for a purpose, namely to deter aggression and, if deterence fails, to successfully wage war. The strategy to achieve this purpose should guide the formulation of system renewal plans. Potential adversaries should be identified and their intentions, war-proneness, capabilities, weaknesses and strategies assessed

to arrive at a strategy that is congruent with foreign policy. Competitive strategy [Englund, 1987], for example, seeks a favorable cost exchange ratio by making obsolete major components of the enemy's defence system. Stealth bombers and SDI are manifestations of this potentially destabilising strategy. Some references on strategic analysis and forecasting are provided in the bibliography.

There are many facets of strategy that affects system renewal plans. Resources for modernisation may be channelled to boost readiness if conflict seems imminent. The danger of provoking or worsening an arms race must be weighed carefully if plans call for a significantly increased capability. The impact of a plan on the economy may also be significant. The B-2 program recommended by the USAF, for example, asks for a whopping seventy-five billion dollars. The impact of modest levels of defence spending on the economy is usually seen to be beneficial. Fredericksen's [1989] analysis, for example, showed a favorable feedback relationship between defence spending and economic growth in Indonesia for the period 1964 to 1985. Economic issues and methodology in arms race analysis are surveyed in Leidy and Staiger [1985].

The link between strategy and procurement is historically lacking in the US (and Singapore). The chairman of a Defense Resource Management Study in 1979, for example, declared that there is broad agreement that the first P in PPBS is silent [Rice, 1979]. The Packard Commission in 1986 stated:

> ... there is a great need for improvement in the way we think through and tie together our security objectives, what we spend to achieve them, and what we buy. The entire undertaking for our nation's defence requires more and better long-range planning. This will involve concerted action by our professional military, the civilian leadership of the Department of Defense, the President, and the Congress.

> Today, there is no rational system whereby the executive branch and the Congress reach coherent and enduring agreement on national military strategy, the forces to carry it out, and the funding that should be provided - in light of the overall economy and competing claims on national resources. The absence of such a system contributes substantially to the instability and uncertainty that plagues our defence program. These cause imbalances in our military forces and capabilities and increases the cost of procuring military equipment.

This thesis seeks to improvise a link between strategy and force/resource planning by incorporating strategic outlook into system renewal plans. The cost and effectiveness of alternatives of interest are projected into the future to make for more forward-looking plans. Figure 2.1 illustrates the links between strategic issues and system renewal planning. It is hoped that at some future time system renewal plans can be aggregated and linked to arms race models, strategic analysis models, econometric models, etc. to provide a higher level of optimisation.

Technology pushes system renewal because it holds the key to one's edge over the enemy. However, excessive emphasis on performance exacts an inordinate cost. Figures 2.2 and 2.3 [Gansler, 1989] show the cost histories and performance growth respectively of a series of U.S. fighter and attack aircraft. The performance assessment methodology used in Figure 2.3 is explained in Chapter 4. As can be seen, the difference in unit cost between high-end aircraft (e.g. F-15A, F-18) and low-end ones (e.g., F-16A, A-7A) had grown significantly through the years. Performance growth was however much more modest, indicating that cost-effectiveness of high-end aircraft had deteriorated relative to that of the low-end ones. Figure 2.3 suggests that the performance of the first operational units of a low-end aircraft lags that of high-end ones by only five years. It also implies that technological superiority over Soviet counterparts could have been maintained using lower-risk, lower-cost aircraft. The lower cost translates into more aircraft, which may matter more in terms of

military results. Expensive high-performance or multi-role assets also require intricate defences as they are too valuable to lose. Quality must also be traded off against quantity when selecting alternatives in a system renewal plan. This tradeoff can be accomplished within the model to be introduced in the following chapters by denoting quantity as a performance parameter. The impact of future innovation on the cost-effectiveness of alternatives of interest is projected so that optimal numbers of the right alternatives will be procured at the right time.

The question of how far to push technology in a procurement program has major cost and effectiveness implications. Figure 2.4 illustrates how the technological frontier for a certain type of system may advance with R&D effort. Point A is typical of a target set to ensure the ability to counter probable threats over a long horizon. Due to the risks involved, it is likely in this case to end up somewhere inside the area bounded by the points A, B and C. The less ambitious and better plan would be to seek to quickly and cheaply arrive at say point D first, then improve incrementally to point A. Having such pre-planned product improvements (P^3I) requires good forecasts of likely future upgrades. The model to be introduced facilitates the selection and scheduling of such upgrades. The reader may be interested in the 1984 report by the U.S. Defense Science Board entitled "Improved Defense through Equipment Upgrades: The U.S. and Its Security Partners".

Requirement specifications largely determine the technological content of a program. These requirements may not be the result of careful study. In fact, they understandably tend to reflect the psychological comfort levels of those who have to deal with the exigencies of war. After all, it never hurts to be able to go the extra mile. Accordingly, the best of various candidate systems often becomes the "requirement". The importance of specifying objective, mission-oriented requirements cannot be overstressed.

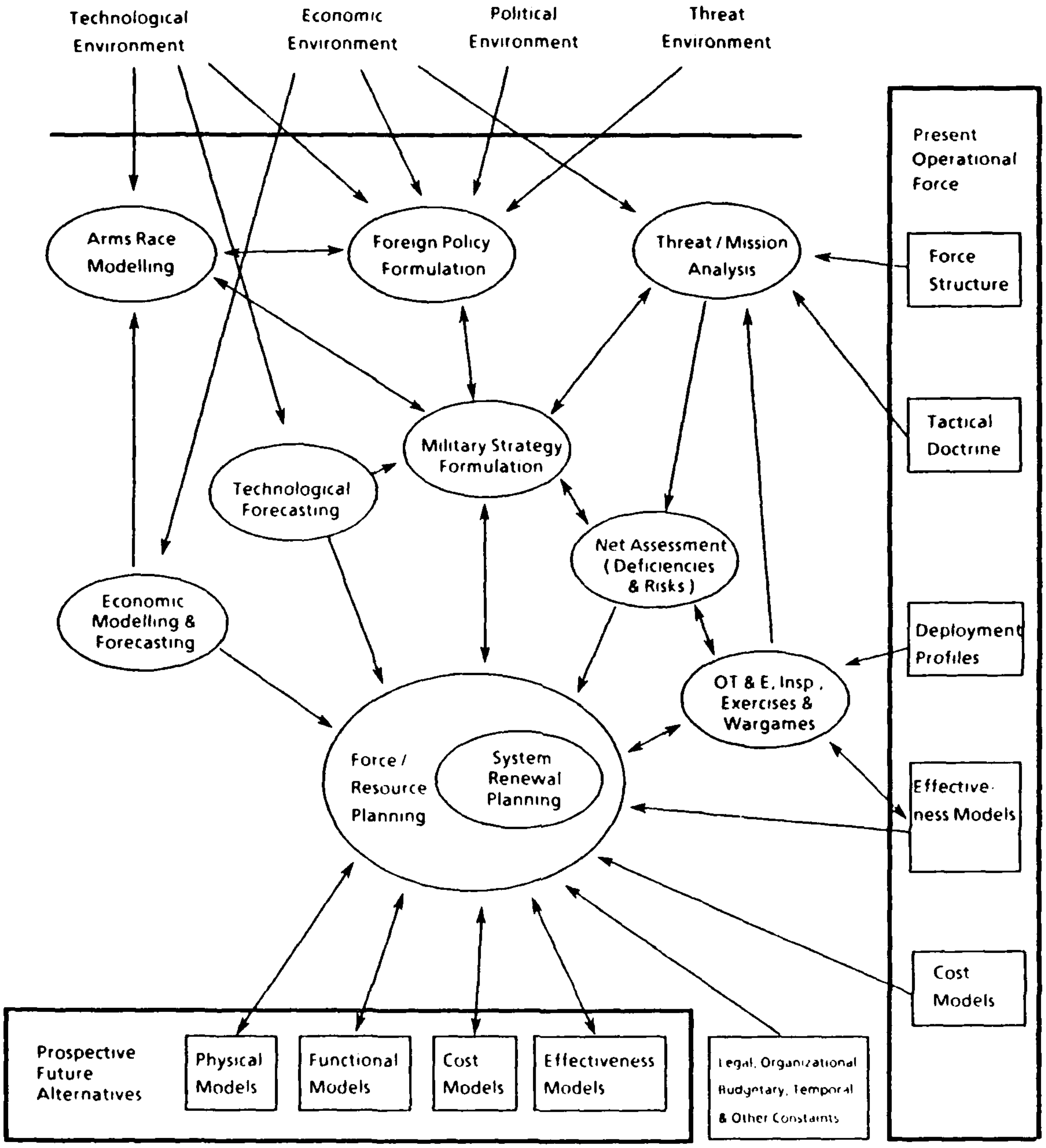


Figure 2.1 : System Renewal and Related Issues

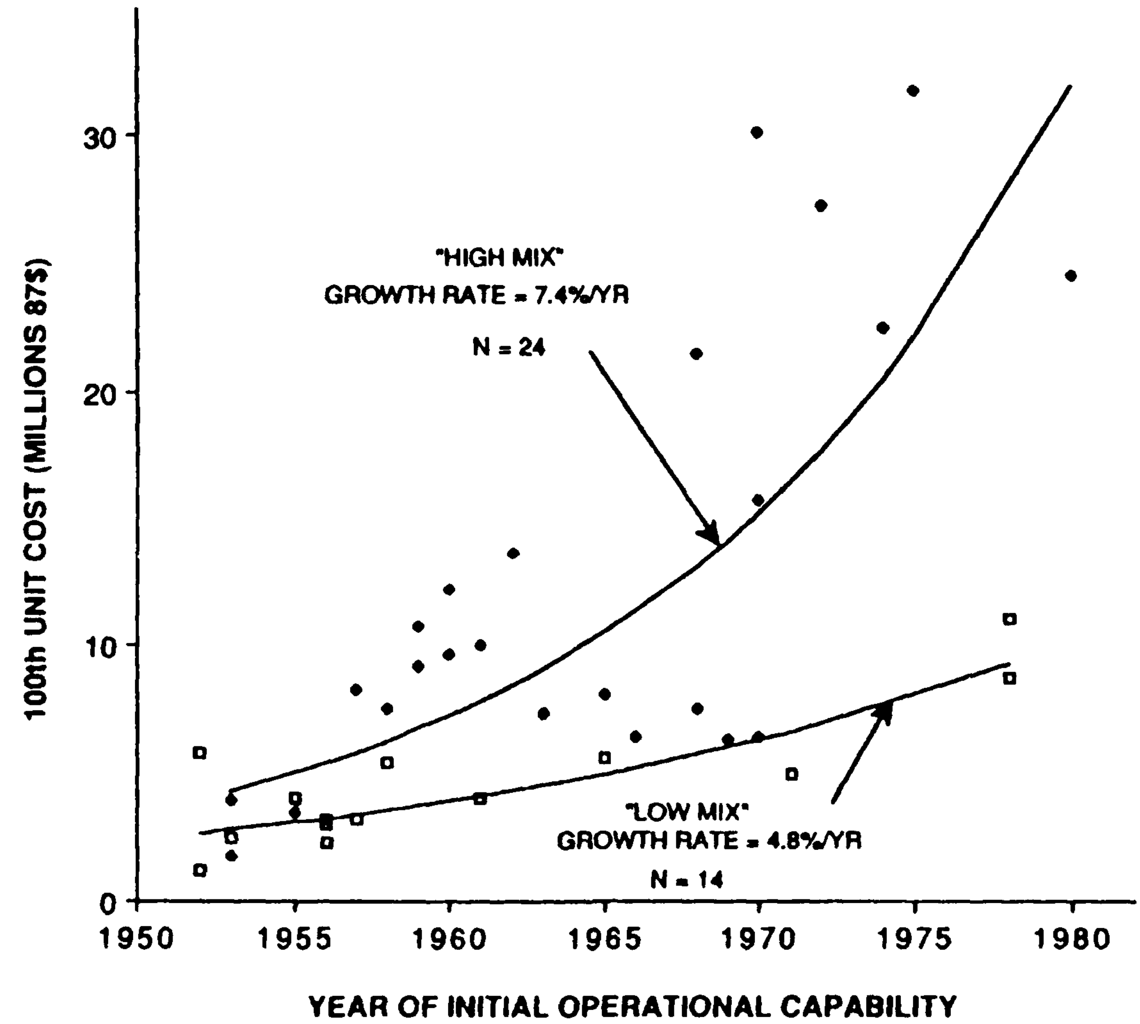


Figure 2.2 : Cost Growth in U.S. Fighter/Attack Aircraft

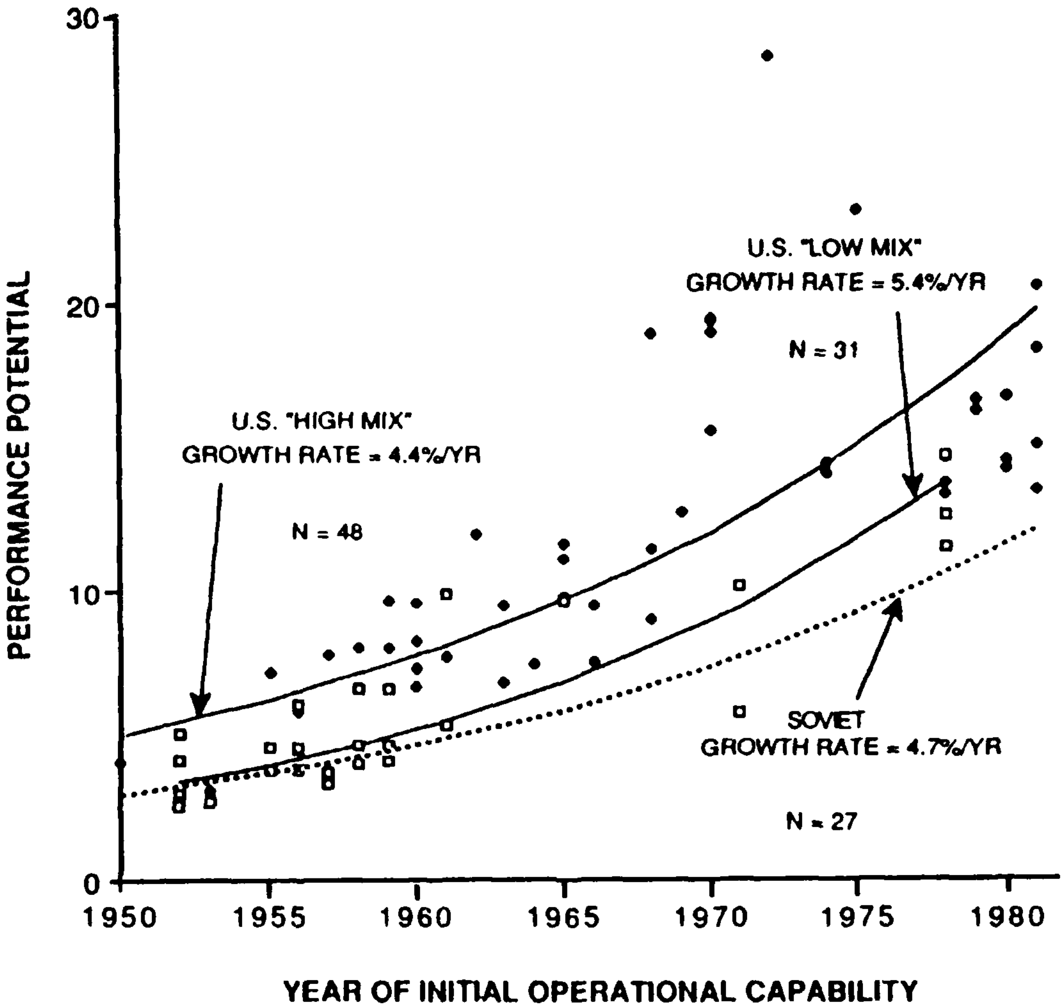


Figure 2.3 : Performance Comparison of U.S.
& Soviet Fighter/Attack Aircraft

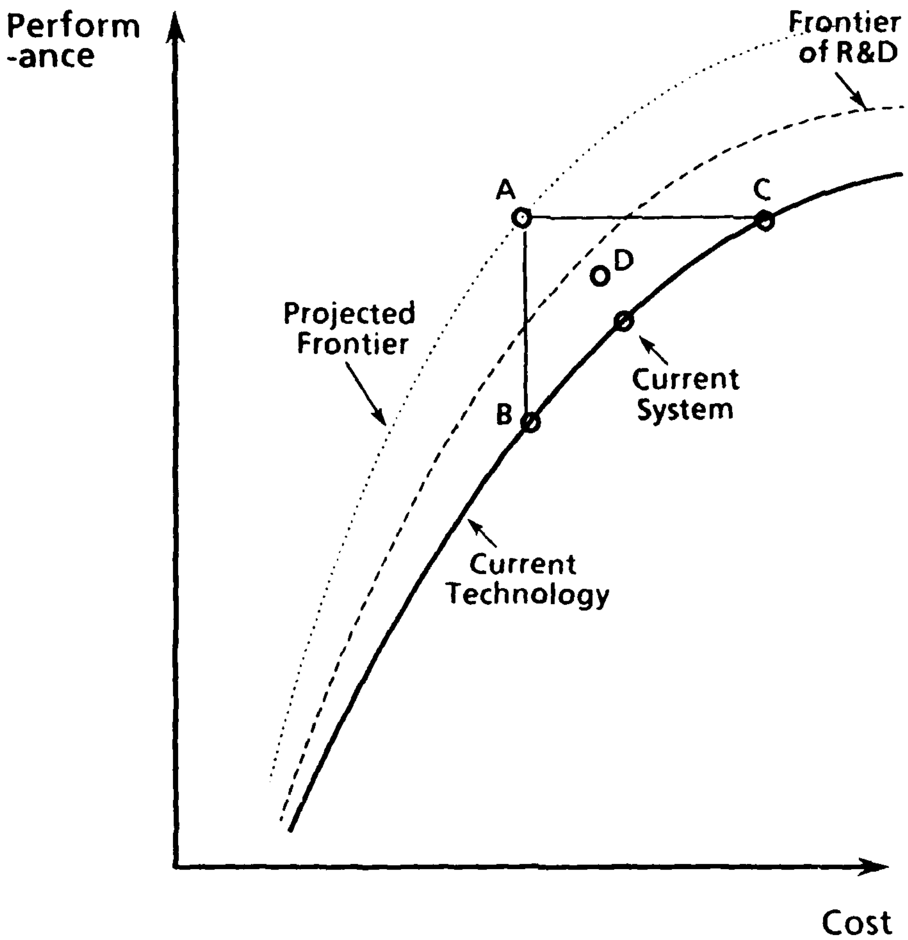


Figure 2.4: Technology Frontier and R & D

C. ECONOMIC ISSUES

Cost-effectiveness of alternatives are dependent on future interest rate, foreign exchange rates, inflation rate, resale/salvage/scrap market condition and budget allocations. The U.S. Department of Defense publishes forecasts of inflation indices for various categories of military hardware which can be used in system renewal planning. DoD would of course like to estimate conservatively (high inflation) so as to get more money to play safe in case it actually is high. However, in times of high inflation, there is in fact considerable political pressure for lower estimates in order to suppress defence budget growth projections. The cumulative inflation from

1978 to 1981 was 45 percent, while the inflation estimated in the DoD budget was only 28 percent [Gansler, 1989]. Therefore one must exercise discretion in using the inflation indices.

Assuming a common interest rate for all programs does not make for equitable comparison as alternatives with different life-spans and cost profiles are affected differently. One should try to forecast the rate as accurately as possible to avoid biased results. As economic factors such as interest rates, foreign exchange rates and market conditions are very difficult to estimate, sensitivity of solutions to their likely fluctuations should be tested in actual system renewal planning.

Adoption of a longer term perspective in system renewal planning should be matched by the adoption of a multi-year budget. Procurement of needed quantities of a system is usually most economical at a certain rate. An optimal system renewal plan may involve humps in budgetary outlays. The minimum efficient rate of production for F-15 aircraft, for example, is 120 per year. However, DoD was allowed only 41 per year [Gansler, 1989]. This U.S. practice of stretching out programs to smooth out the humps tends to lead to gross inefficiencies in procurement. The floating of treasury bonds, for example, may be a better way to achieve a more efficient procurement program. For multi-year budgets to work, accurate cost estimates are necessary. Buying off-the-shelf items, adopting low-risk approaches (e.g., by emphasizing P^3I) and designing to cost are collaborative means towards this end.

D. MODELLING ISSUES

Military system renewal planners have to grapple with problems of multi-facetedness, vagueness, uncertainty and subjectivity. Even if the effectiveness of a given alternative can be summarised by a single MOE, one has still to consider its

cost and probable service life. The system renewal problem has therefore at least three dimensions – effectiveness, cost and useful life. Often, service life is simply assumed and net cost is amortised into a rate over this period for evaluations. However, advocates of an alternative will tend to assume a longer life than opponents. Instead of assuming when an alternative will become obsolete, the model to be presented derives the service life as an output based on economic, technological and military (requirement) forecasts. This should make for more realistic and equitable evaluations.

Risks due to uncertainty can be assessed by testing the sensitivity of solutions to possibilities learned from experience. Dominance or robustness of a solution would provide some assurance of its validity under a range of expected scenarios. The quality of experience is of critical importance for such risk assessment. As such, qualified experts should be consulted in the formulation of scenarios.

Besides multi-facetedness and uncertainty, a planner has to contend with problems of vagueness. Strategic analysis may highlight the need to heighten readiness in the coming years but such qualitative goals do not readily lend themselves to mathematical modelling. Even if readiness can be precisely quantified by a parameter, there may not be consensus concerning what constitutes the proper level of readiness. Fuzzy set and logic theory offer means to bridge the gap between quantitative and qualitative reasoning, thus linking strategy formally to procurement planning. The efforts of J. Dockery [1985] is an example of work done in this area. Karprzyk and Orlovski [1987] and Zimmerman, et al., [1984] also discuss new paradigms more suited to situations where vagueness and uncertainty are clearly present. The problem of vagueness is not considered in this thesis but may be addressed in future embellishments.

Although the exercise of human judgment is essential in system renewal planning, the subjectivity involved must be managed well to reduce the possibility of bias (conscious or otherwise). The problems encountered in assessing utility functions, for example, were surveyed by Hershey et al., [1982] and Farquhar [1984]. It should, however, be noted that intuitive (subjective) judgment of experts may in certain cases prove superior to analytical studies [Hammond, 1987]. Human behavioral aspects are important in a real application, but they are not considered in this thesis because the cases studied are hypothetical ones meant for illustrating the model that was developed. Utility functions, for example, were assumed to be explicitly defined even though such functions are difficult to assess accurately in practice.

The horizon of optimisation is an important issue in modelling system renewal. Very often, this horizon is either fixed at some arbitrary value or taken to be infinity. Both practices suffer from serious flaws. Choosing horizons that are a small non-integral number of life-spans would produce incorrect results. This occurs, for instance, if the horizon for a system with a typical lifespan of ten years is set to, say, twenty-five years. Assuming an infinite horizon is clearly unrealistic. There are procedures that allow one to find the horizon beyond which the decision for the first change remains optimal. However, these so-called "planning horizon procedures" are essentially also based on the infinite horizon assumption. This thesis takes a different approach, namely the finite-stage approach (from dynamic programming), in which the optimisation horizon is a variable output given by the years spanned by a sequence of systems.

Modelling the effectiveness of a military system is sometimes confused with predicting the outcome of its use in battle. The two are related but not synonmous. As an example, let us suppose that a certain armour unit has the MOE structure shown in Figure 2.5. The outcome in a given battle scenario may be described

by the number of own and enemy losses. Neither of these numbers expresses fully the effectiveness of the force. An abstract figure of merit would have to be computed from these numbers based on judgment concerning what constitutes success. Therefore, one might say that battle outcomes are predicted by combat modelling whereas effectiveness is evaluated by "combat value" modelling. The abstract figure of merit may be said to be the MOE, and performance parameters that determine this value may be said to be the measures of performance (MOPs). This distinction is, however, an artificial one as the MOPs may collectively be considered to be a vector-valued MOE. Accordingly, MOE and MOP in this thesis are both taken to mean the same thing – key performance parameters that determine the effectiveness of a system. In the example shown in Figure 2.5, the MOEs would be range, accuracy and lethality if these parameters are the ones that have major effects on effectiveness.

E. ORGANISATIONAL ISSUES

System renewal plans may be developed for many different levels, ranging from a single equipment to an entire task force. Unless they are coordinated such that the objectives of upper echelons are considered by lower echelon planners, sub-optimal or even counterproductive plans are likely to be made. Most resource allocation models do not consider the organisation as a factor in the decision process; that is, they assume a monolithic decision-making entity. The same decision-makers are assumed whether the subject of planning is a single artillery gun or an infantry division. Ruefli [1974] surveyed several economic and management science models that provide remedy for this unrealistic assumption by explicitly reflecting organisational structure in the model. The Dantzig-Wolfe model [Dantzig and Wolfe, 1960] is the best known of the classical models. In more recent years, models such as the one by

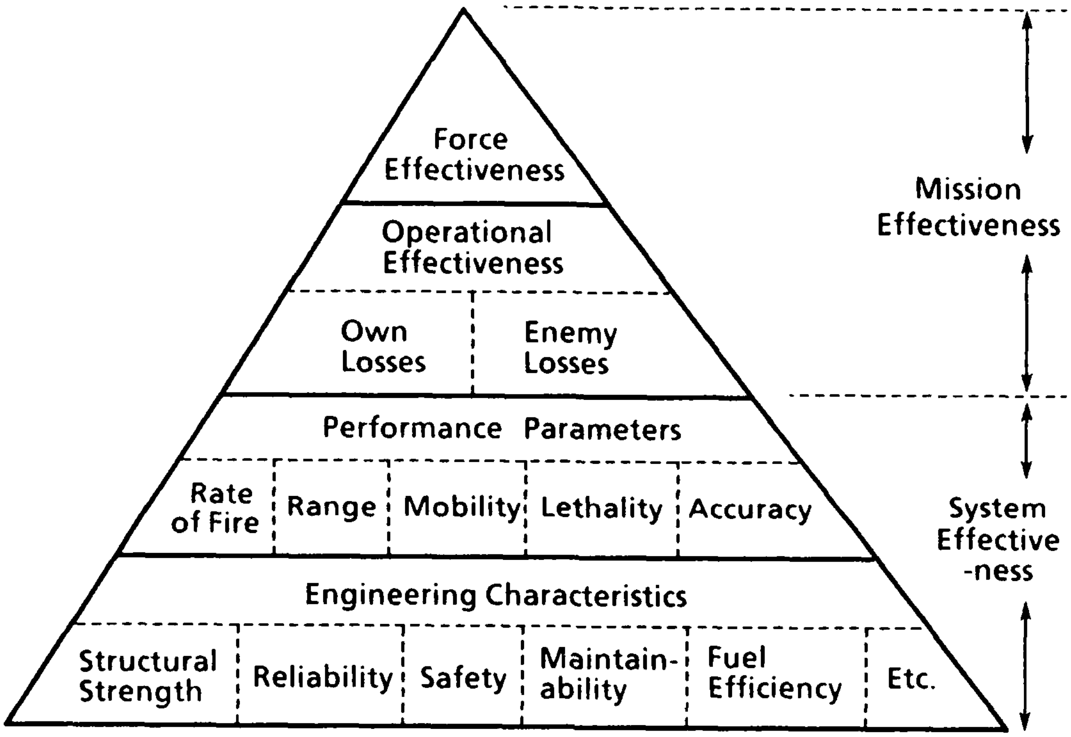


Figure 2.5 : Hierarchy of MOEs

Source : Modified version of the diagram from
"Notes on MOEs" by E.B.Rockower, Aug. 1985.

Cassidy et al., [1971] that are based on behavioral theories have emerged. Organisational issues are not considered in this thesis as the model is still a conceptual one that is not ready for organisation-wide implementation.

F. LITERATURE SURVEY

No literature suitable for military system renewal planners could be found as all those surveyed were commercially oriented ones that subjugated performance considerations under cost. Most of them consider only replacement alternatives.

The earliest of these were based on simple calculations and differential and integral calculus. Examples are Preinrich's Constant Chain Model [1940] and Terborgh's MAPI system [1949]. In more recent years, methods such as dynamic programming, Markov chains and Pontryagin's maximum principle have become more popular. The first such model was introduced by R. Bellman [1955] using dynamic programming. Howard [1960] used a policy-iteration method to solve multi-stage decision problems in connection with Markov processes. Numerous articles conerning stochastic models were published in the 1960's. A survey of the treatment of stochastically failing equipment was compiled by Jorgenson et al., [1967]. Naslund [1966] was the first to apply the maximum principle to the replacement problem. Thomson [1968], Rapp [1969], Sethi [1970] and many others used these so-called "optimal control" theory models that uses the maximum principle. There are numerous variants in replacement models, the assumptions of which were grouped by Luxhoj and Jones [1986] in a general framework. Some of the works not referenced in this survey may be found in the bibliography.

Some of the more noteworthy recent publications that explicitly considered technological advances are as follows:

1. R.C. Stapleton et al., [1972] examined the effects of different forms of technological change (change in purchase price, resale value, operating costs and rate of deterioration) on costs using dynamic programming. This work provided the author of this thesis with basic ideas on how to model the impact of technological progress on cost.

2. S. Chand and S. Sethi [1979 and 1982] applied the planning horizon procedure developed by H.M. Wagner and T.M. Whitis [1958] for the dynamic lot size model to the replacement problem. It allows one to obtain the first replacement

time for an infinite planning horizon based on the optimal policy for a finite horizon. Technological advances is forecasted for this equivalent finite horizon. The 1982 paper, which extends the first to the case of multiple alternatives, treated upgrades within the same framework as replacement alternatives. This idea led to the adoption of a common framework for all alternatives in this thesis.

3. T. Goldstein et al., [1988] examined the influence of a forthcoming new and better machine (based on an expected technological breakthrough) on the system renewal decision. Each year, if the new machine does not appear, a decision is made to either continue with the incumbent and wait for the better machine, or buy a new version of the incumbent. The model determines the optimal age for replacing the existing machine. This model ignores evolutionary changes that characterises technological innovation and thus was not adopted in this thesis.

4. Y. Kusaka [1985] showed a method for deciding whether to keep or replace the existing machine at the present time without determining the sequence of subsequent replacement times. A joint paper with H. Suzuki [1988] expanded on the earlier evaluation system by introducing the concept of "control limit" policy. Kusaka's method was not adopted in this thesis as the provision of estimates concerning future renewals is deemed to be a useful feature.

III. THE MODEL

A. INTRODUCTION

As evident in the previous chapter, many complex issues impinge upon decisions concerning systems renewal planning. Literature searches have failed to uncover any model suitable for system renewal planning in the military. The dynamic system renewal planning (DSRPM) model to be presented in this chapter is a first-cut attempt to weave a unifying framework spanning some of the more quantitative issues involved in systems renewal planning. The overall approach is outlined first, followed by theoretical underpinnings of the model.

B. APPROACH

The adopted approach is to use a versatile methodology, namely dynamic programming augmented by the Lagrangian relaxation technique, to *explicitly model* the effects of aging, technological advancement, and changes in capability requirements. The methodology operates on an acyclic directed network of the kind shown in Figure 3.1. This network representation of the system renewal process is unique to this thesis. As this network lies at the heart of the model, a brief description is in order before we move on to the other parts of the model.

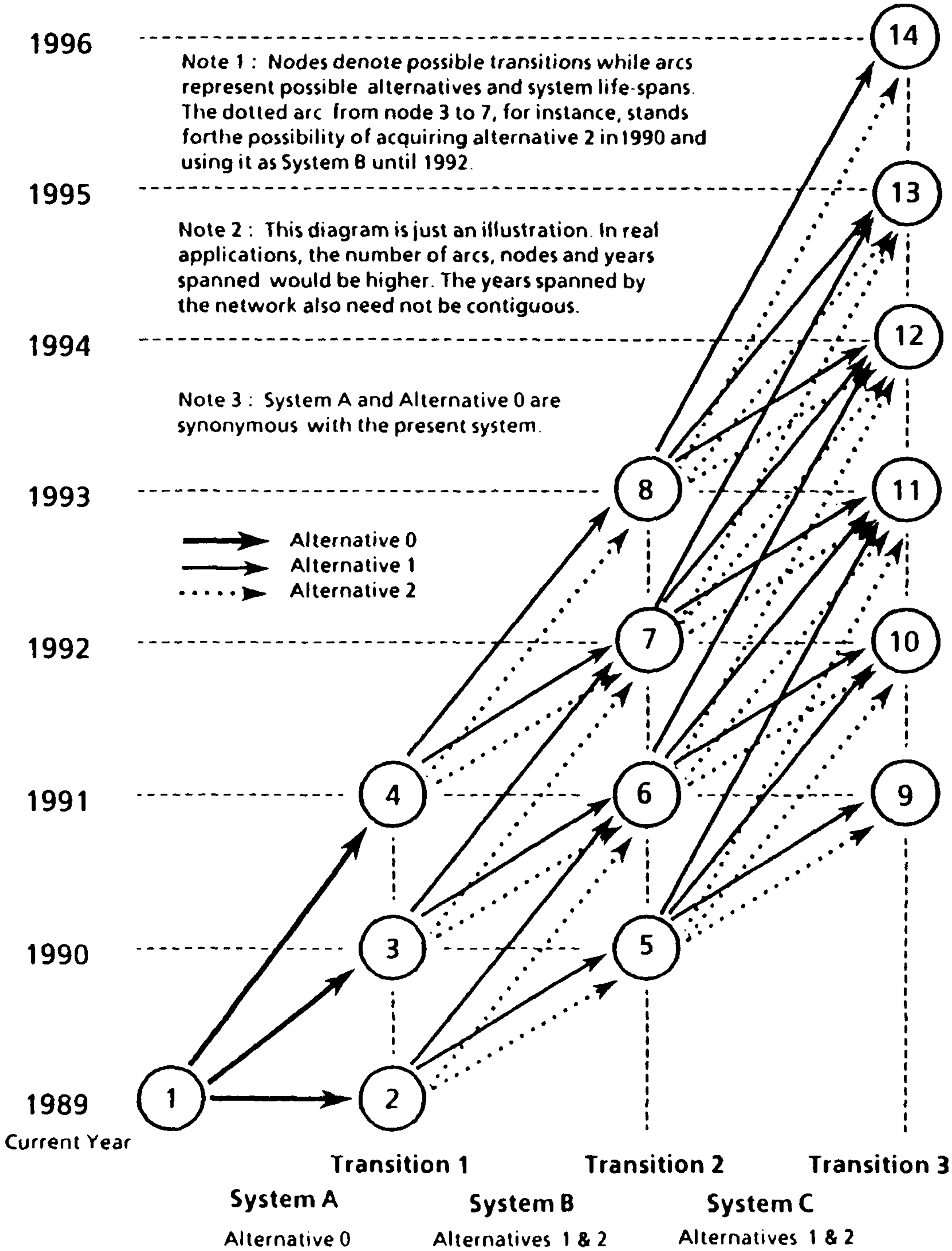


Figure 3.1 : Network Representation of System Renewal Process

The network represents the system renewal process involving the selection of a succession of systems to fulfill some capability requirements. The root node 1 represents the present system (System A) in the current year. Each of the arcs emanating from it represent a possible residual life-span of this system. These arcs terminate on a column of nodes representing possible points in time for transition to the next system (System B). Transitions may be replacements or upgrades. Similarly, arcs extending from these nodes to an adjacent column of nodes represent the possible years for transition from System B to System C. The number of arcs connecting each pair of nodes corresponds to the number of alternatives that may be selected for System B; likewise for System C. Thus if cumulative cost and effectiveness of using a given alternative over a given life-span are assigned as attributes to the associated arc, optimisation for the three systems reduces to one of finding the "best" path through the network.

Finding the "best" path constitutes solving a three stage dynamic programming problem. If cost is set to a very large number whenever an alternative ages such that one or more performance parameters at the end of a given life span fails to meet stipulated requirements, then dynamic programming yields the solution *that meets the requirements* at minimum cost. However, if one seeks the optimal trade-off between cost and effectiveness, then the problem becomes a multicriteria one. This problem can be solved using the Lagrangian relaxation technique by formulating this problem as one of maximising effectiveness given a certain budgetary limit on cost. Details of this technique are given in section D of this chapter. The "best" path can also be solved using linear programming formulation of the network flow problem. However, the dynamic programming formulation has more intuitive appeal and lends itself easily to incorporation of lead-time, discounting and other considerations.

The aging process is modeled by discounting performance and cost characteristics over time, based on empirical parametric relationships. What these characteristics will be for a given alternative acquired new in a certain year is projected based on technological trends. Forecasts of inflation and foreign exchange rates are also factored into the projected acquisition, maintenance and other costs. All outlays are converted to current year dollars based on forecasted interest rates. The projected rates may vary from year to year but a steady trend is assumed beyond an arbitrary forecast horizon. Performance requirement levels may also be stipulated for each year based on analysis of politico-military trends. A unique set of life-cycle cost and effectiveness measures is thus associated with the network for each scenario expressing a given set of expectations concerning relevant future trends. The minimum cost solution and efficiency boundary for each scenario can then be obtained by applying dynamic programming and Lagrangian relaxation to the corresponding network. The efficiency boundary expresses the upper bound on effectiveness over the entire spectrum of life-cycle cost spanned in a given scenario (Figure 3.2). The point on this boundary that yields the highest effectiveness-to-cost ratio is the solution that gives the most bang for the buck. As the boundary is piecewise linear, all points along a line segment may qualify if extrapolation brings the line through the origin. Otherwise, a Lagrangian solution point at the intersection of two line segments will qualify.

The reader may wonder why a three stage process is adopted in this model. The model itself does not restrict the user to any number. Rather, the matter is one of judgment concerning the credibility of long-term forecasts. Although it is desirable to optimise over as long a stream of systems as possible, it is also futile to try to visualise the distant future. A two-stage model comprising the present system and its immediate successor is satisfactory as far as a reasonable optimisation

horizon goes. A three-stage model would be preferable as it allows realistic bounds to be developed for the immediate successor's economic-technological life. The cost of competing alternatives can therefore be more equitably compared since their amortisation periods may be more accurately estimated. Infinite horizon models meant for static environment problems are clearly not suitable for our purposes. Accordingly, assumptions of monotonicity, contraction, boundedness, etc., which are required for asymptotic stability of such models [Henig 1978, Beckmann 1968, Boudarel 1971] need not be made.

It may be noted that a long lead time often precedes transitions, be they upgradings or replacements. Lead time of an alternative is defined to mean the minimum number of years by which the initiation of acquisition must precede the achievement of initial operating capability (IOC). By setting to infinity the cost of alternatives that cannot be introduced because of insufficient preceding lead time, we can avoid generating solutions contradicting lead time requirements. This check is made not only for transitions from the present system to its immediate successor, but also for subsequent ones. The latter requires the assumption that initiation of a transition never begins before the preceding one even takes place. A path in the network is thus deemed infeasible if there is any arc representing a system life shorter than the lead time required by its successor.

While no one can reliably predict the future, one ignores future possibilities and trends only to one's disadvantage. Taking calculated risks after examining a broad range of scenarios is the only realistic approach to handling uncertainties about the future. For this purpose, the flexibility of the model presented is a valuable asset. Long-range projections can be varied more than near-term ones to account for greater uncertainty in these projections.

It should be emphasized that the focus of analysis is on the timing and choice of alternatives for the first transition, the optimality of which is affected less by inaccuracies in long-range forecasts than short-term ones. By updating the scenarios annually for changes in the perception of qualified experts, rolling plans can be developed for system renewal decisions to be made optimally and in a timely fashion. For this reason, the model is named the Dynamic System Renewal Planning Model (DSRPM).

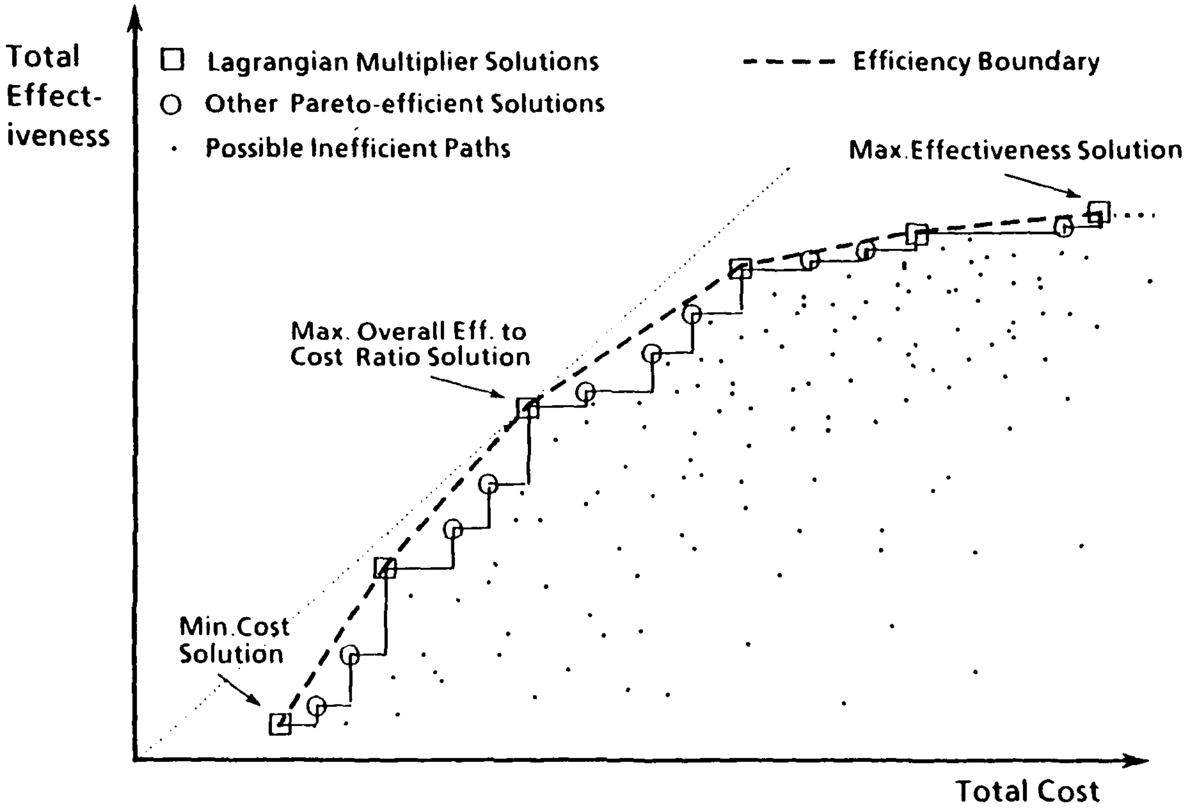


Figure 3.2 : Domination of Solution Space by Efficiency Boundary

C. ASSUMPTIONS

For the purposes of this thesis, the following assumptions have been used:

- A steady state exists beyond an arbitrary forecast horizon where all projections are either constant, linear or harmonic. This assumption expresses the lack of detailed knowledge about the remote future.

- Cost and performance parameters can be measured deterministically and utility functions can be obtained explicitly. (Note: This assumption would be relaxed in future embellishments incorporating stochastic models and implicit approaches to utility modeling.)

- An upgraded system is a new system with acquisition cost equal to the direct upgrading costs plus the salvage or resale value of the original system in the previous year. A new acquisition with no precedent is simply one in which the incumbent system is a null or dummy system. With this assumption, upgrading, replacement and new acquisition alternatives are integrated within a common framework.

- Acquisitions (upgrading or replacement) and their associated outlays occur at the beginning of a transition year. The old system is disposed of at the end of the year. This definitive assumption provides for proper costing of the metamorphic process by which a new system achieves initial operating capability (IOC) while the old is prepared for disposal. Disposal does not really occur in an upgrading, but the new capability is still assumed to be achieved at the end of the transition year.

- No transition is initiated before the preceding one takes place, as was explained in the previous section.

One should note the small number and unrestrictive nature of the assumptions made in the model. This is a direct consequence of the versatility of the methodology employed. There are other assumptions needed to model particular alternatives and scenarios such as those pertaining to utility functions, nature and impact of trends, etc., but these are not generic to the model discussed.

D. METHODOLOGY

Dynamic programming and Lagrangian relaxation are the cornerstones of the model's integrity and the source of much of its power. This section explains these key techniques as applied to finite discrete decision processes. As methodologies concerning forecasting, cost estimation and other components of the model may vary according to the peculiarities of the application, these will not be discussed. The reader is referred to the bibliography for materials on these aspects of the model.

1. Dynamic Programming

Borrowing the notation used by the pioneering developer of dynamic programming, Richard E. Bellman, [Bellman and Kalaba, 1965], we begin by examining the important notion of policy in the context of system renewal. If a decision d_i in the i^{th} stage results in a transition from a state y_i to a state y_{i+1}, then an n-stage process may be represented as

$$\begin{aligned} y_1 &= T(y_o, d_o) \\ y_2 &= T(y_1, d_1) \\ &\vdots \\ y_n &= T(y_{n-1}, d_{n-1}) \end{aligned} \tag{3.1}$$

In the 3-stage system renewal process depicted in Figure 3.1, for instance, the process of operating the present system for a year, then acquiring alternative

1 to use for two years before acquiring anew another alternative 1 for a further two years use would be represented by a path $P_{1,3,7,12}$ of unbroken line arcs passing through nodes 1, 3, 7 and 12.

Suppose we are concerned with maximizing a prescribed scalar function of the states and the decisions:

$$R(y_0, y_1, y_2, \cdots, y_n;\ d_o, d_1, \cdots, d_{n-1}) \tag{3.2}$$

This so-called criterion function, in the case of a system renewal process, may be the cumulative expected return accrued from acquiring and operating a particular succession of alternatives, i.e., traversing a given path in the network. Without an optimal rule as to how decisions should be made, the only way to obtain the maximum of R and its associated path is by exhaustive enumeration along all possible paths. Effort is much reduced with the use of rules in the form

$$d_k = d_k(y_0, y_1, \cdots, y_k;\ d_0, d_1, \cdots, d_{k-1}) \tag{3.3}$$

These functions are called policy functions, or simply policies. A policy that maximizes the criterion function R is called an optimal policy.

Let us consider, in particular, policies which depend only on the current state, k, that is policies of the form

$$d_k = d_k(y_k) \tag{3.4}$$

This additional simplification is possible only when the structure of the criterion function R has the important property of divorcing the past from the future. Examples of criterion functions with this "separable criterion" property include

$$\sum_{i=0}^{k} C(y_i, d_i) \tag{3.5}$$

$$\text{and} \quad \prod_{i=n}^{k} r(y_i, d_i) \tag{3.6}$$

The first example is of the most common type of criterion. The usual criterion of cumulative cost or cumulative returns used in system renewal is of this variety. The reliability of series systems would perhaps come to mind in the case of the second one. An example of a criterion function that does not have the separability property is that of an overall ratio, that is,

$$\frac{\sum_{i=0}^{k} E(y_i, d_i)}{\sum_{i=0}^{k} C(y_i, d_i)} \tag{3.7}$$

The use of overall cost-effectiveness ratio as a criterion in the renewal process would thus require decisions to be based not only on the current state but also on the path leading to that state.

When the criterion function used has this vital separability property, the optimal policy is characterized very simply by the following principle of optimality:

$$(y_o, y_1, \cdots, y_m, y_{m+1}, \cdots, y_n) \text{ is optimal} \Rightarrow (y_0, y_1, \cdots, y_m) \text{ is optimal} \tag{3.8}$$

This intuitive result can be proved by contradiction. Suppose that for the $(m+1)$ stage process, $(y_o, y_1, \cdots, y_m)$ is not optimal. Specifically say $(x_0, x_1, \cdots, x_m)$ is optimal. Then $(x_0, x_1, \cdots, x_m, y_{m+1}, \cdots, y_n)$ is better than $(y_0, y_1, \cdots, y_m, y_{m+1}, \cdots, y_n)$. But this contradicts the original premise that $(y_0, y_1, \cdots, y_m, y_{m+1}, \cdots, y_n)$ is optimal. Therefore, expression 3.8 must be true. Using the principle, one obtains for the examples given by expressions 3.5 and 3.6 the following optimal policies:

$$f_{k+1}(T(y_k, d_k)) = \max_{d_k} [c(y_k, d_k) + f_k(y_k)] \tag{3.9}$$

$$f_{k+1}(T(y_k, d_k)) = \max_{d_k} [c(y_k, d_k) f_k(y_k)] \tag{3.10}$$

where $f_i(y_i, d_i)$ is the criterion function in state i obtained using an optimal policy.

Dynamic programming hinges around the formulation of optimal policies to enable solutions to be found by systematic recursion [Beckmann, 1968]. A solution may be given in terms of the sequence of criterion functions $\{f_i(y_i)\}$ or the sequence of policy functions $\{d_k(y_k)\}$. Each determines the other, although one should note that there may be several optimal policies yielding the same sequence of criterion functions. A policy may also be satisfied by one or more solutions. Only when the solution is unique is the policy a necessary and sufficient condition for optimality. Otherwise, it is necessary to compare the solutions using additional considerations such as risk, expected life-span, etc., to define the optimal solution.

Being a flexible and potent tool, dynamic programming has many variations. In stochastic dynamic programming, the next state is chosen based on conditional transition probabilities and the criterion function is given as a random variable, usually the mean of possible rewards [Ross, 1983]. Variations with vector-valued criterion functions have been developed [Henig, 1978], but these multicriteria dynamic programming models are still not as widely applied as the stochastic variants. Although these multicriteria models could be used in system renewal problems to obtain dominating (Pareto-efficient) solution sets, it is simpler, more useful, natural and elegant to use the Lagrangian relaxation technique in such problems, as shall be shown in the following section.

2. Lagrangian Relaxation Technique

Two conceptual approaches used in systems analysis are either to fix effectiveness and minimize cost or fix the budget and maximize effectiveness [Fisher, 1970]. Suppose we choose the latter and formulate the system renewal problem as

$$\max_{d_0,\cdots,d_n} \sum_{i=0}^{n} E(y_i, d_i) \tag{3.11}$$

subject to

$$\sum_{i=0}^{n} C(y_i, d_i) \leq \text{Budget} \tag{3.12}$$

where $E(y_i, d_i)$ and $C(y_i, d_i)$ are the life-cycle effectiveness and cost respectively of making a decision d_i in state y_i. Units for the former are utiles, while that of costs are dollars. In the system renewal process shown in Figure 3.1, for example, if the current state is represented by node 3, and the life-cycle effectiveness and cost of acquiring alternative 1 and operating it for two years are 2,100 utiles and \$7m respectively, then $E(3,2) = 2,100$ utiles and $C(3,2) =$ \$7m. The constraint in expression 3.12 may be relaxed by moving it to the objective function with the inclusion of a Lagrangian multiplier λ, thus

$$\max_{d_o,\cdots,d_n} \left\{ \sum_{i=0}^{n} E(y_i, d_i) - \lambda \left[\sum_{i=0}^{n} C(y_i, d_i) - \text{Budget} \right] \right\} \tag{3.13}$$

Noting that expressions 3.5 and 3.13 are of the same form, we know that the optimal policy for maximizing this criterion function is given by the principle of optimality as:

$$f_{k+1}(T(y_k, d_k)) = \max_{d_k} \{[E(y_k, d_k) - \lambda C(y_k, d_k)] + f_k(y_k)\} \tag{3.14}$$

Therefore, for any fixed λ, conventional dynamic programming may be used to obtain the optimal solution to expression 3.13. Lagrangian relaxation is thus a technique for converting constrained optimisation problems into unconstrained maximization (or minimization) problems [Everett, 1963]. It may also be interpreted as a technique to solve the dual of the original problem given by Equations 3.11 and 3.12, as will be apparent in the following discussion.

To consider the effect of varying λ, let us define the Lagrangian function $L(\lambda)$ to be equal to the objective function given in expression 3.13. That is,

$$L(\lambda) = \max_{d_o,\cdots,d_n} \left\{ \sum_{i=0}^{n} E(y_i, d_i) - \lambda \left[\sum_{i=0}^{n} C(y_i, d_i) - \text{Budget} \right] \right\} \tag{3.15}$$

This piecewise linear function is illustrated in Figure 3.3.

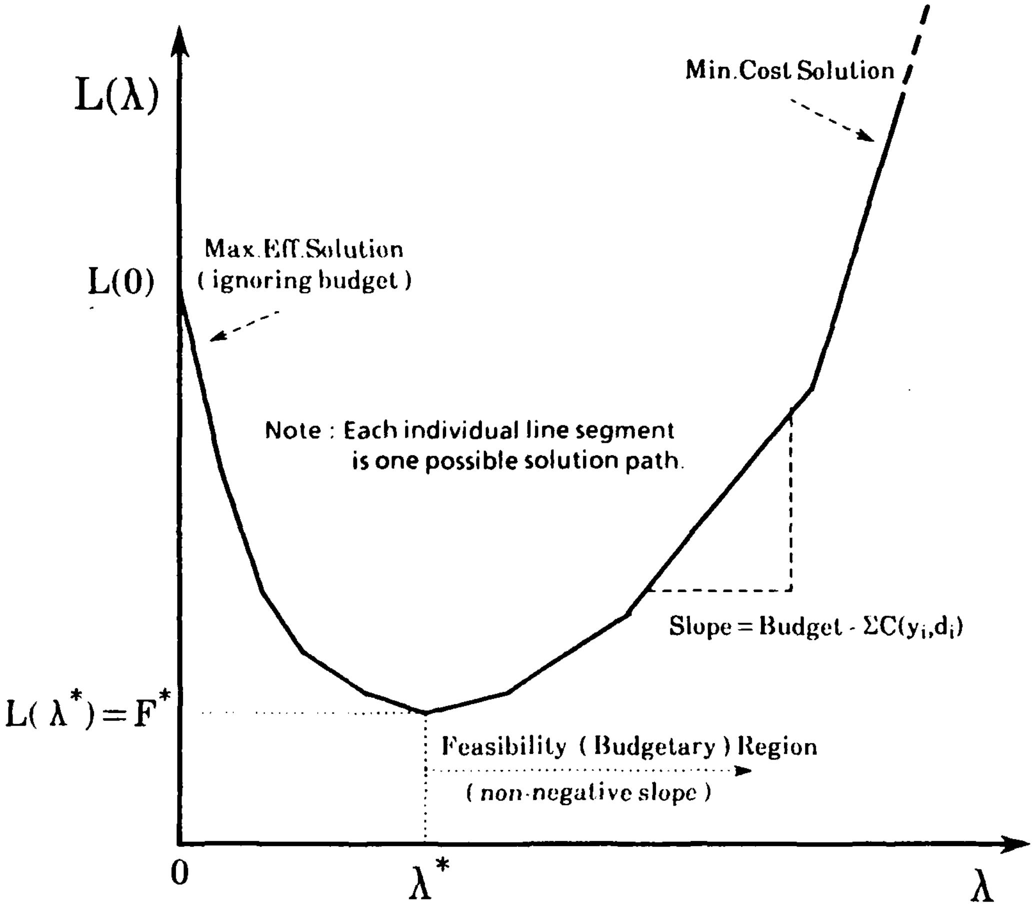


Figure 3.3: Lagrangian Function $L(\lambda)$

When $\lambda = 0$, the budgetary constraint is ignored and we obtain the maximum effectiveness solution to the $(n + 1)$ system renewal problem given in expression 3.13. Denoting the cumulative life-cycle effectiveness and cost of this solution as LCE_0 and LCC_0 respectively, we note that $L(0) = LCE_0$ and that the

slope at this vertical axis intercept is $-(LCC_0 - \text{Budget})$. For marginal increases in λ beyond zero,

$$L(\lambda) = LCE_0 - \lambda(LCC_0 - \text{Budget}) \tag{3.16}$$

which is the equation of the leftmost line segment. When λ reaches a threshold value, the solution changes to one with smaller cumulative life-cycle effectiveness and cost. The next line segment will thus have a lower intercept value and an increased slope. This therefore implies that the Lagrangian function will always be convex for system renewal problems formulated as in expression 3.13.

The Lagrangian multiplier λ has a physical interpretation, namely that of the relative value of cost and effectiveness, i.e., shadow or dual price. Its unit is utiles per dollar. As λ is increased from zero to infinity, the Lagrangian function steps through the entire solution space, from the maximum effectiveness solution to the minimum cost solution. The latter corresponds to the rightmost line segment which extends to infinity. What then is the optimal value of λ? To see this, we first note that for $\lambda \geq 0$, $L(\lambda)$ is an upper bound on the optimal value F^* of the original objective function given in expression (3.11). This is because $\min_{\lambda \geq 0} L(\lambda)$ is the dual of the original problem. The minima of $L(\lambda)$ therefore yields F^*. That is,

$$\min_{\lambda \geq 0} L(\lambda) = L(\lambda^*) = F^* \tag{3.17}$$

This is akin to seeking the constrained stationary points in analog applications of Lagrange's method to differentiable functions.

The minima of $L(\lambda)$ do not necessarily exist. In a commonly observed case, LCC_0 is higher than the budget and the slope at the vertical intercept is negative. As $L(\lambda)$ is convex, λ^* is always finite and non-zero in such cases. If, however, LCC_0 is lower than the budget, that is to say the maximum effectiveness

solution is affordable, then the slope at the intercept will be positive and we obtain $\lambda^* = 0$. Should LCC_0 be higher than the budget and there are no affordable solutions, then there will be no line segments of non-negative slopes, no minima and hence no feasible solution.

The value of λ^* can be found most expeditiously and accurately by the supporting plane method illustrated in Figure 3.4. Given the upper and lower bounds on λ^*, the method involves the extrapolation of the line segments corresponding to these bounds to obtain the intersection value λ_i. The intercept and slope of these line segments are given by the cumulative life-cycle effectiveness and cost respectively of the solution obtained by solving expression (3.13) for the bounding values of λ. The lower or upper bound is replaced by λ_i if the slope of the line segment corresponding to λ_i if the slope of the line segment corresponding to λ_i is negative or non-negative respectively. This process is iterated until λ_i equals one of the bounds. This equality occurs because $L(\lambda)$ is piecewise linear and convex, which enables λ^* to be obtained precisely. The starting lower bound is set to be zero. Any suitably large value of λ that yields a line segment with non-negative slope may be used as the initial upper bound λ_{max}, where

$$\lambda_{max} = \text{No. of nodes x } LCE_{max} \div LCC_{min} \tag{3.18}$$

Experience of the author with similar problems shows this supporting plane method to be faster and more accurate than the commonly used bisection method, and λ^* may be found in only a few iterations even for very large networks with thousands of nodes and arcs.

For each scenario, using the methodology described, we are able to obtain the solution points marking the efficiency boundary shown in Figure 3.2. This is begun by artificially setting a sufficiently high budget to obtain the maximum

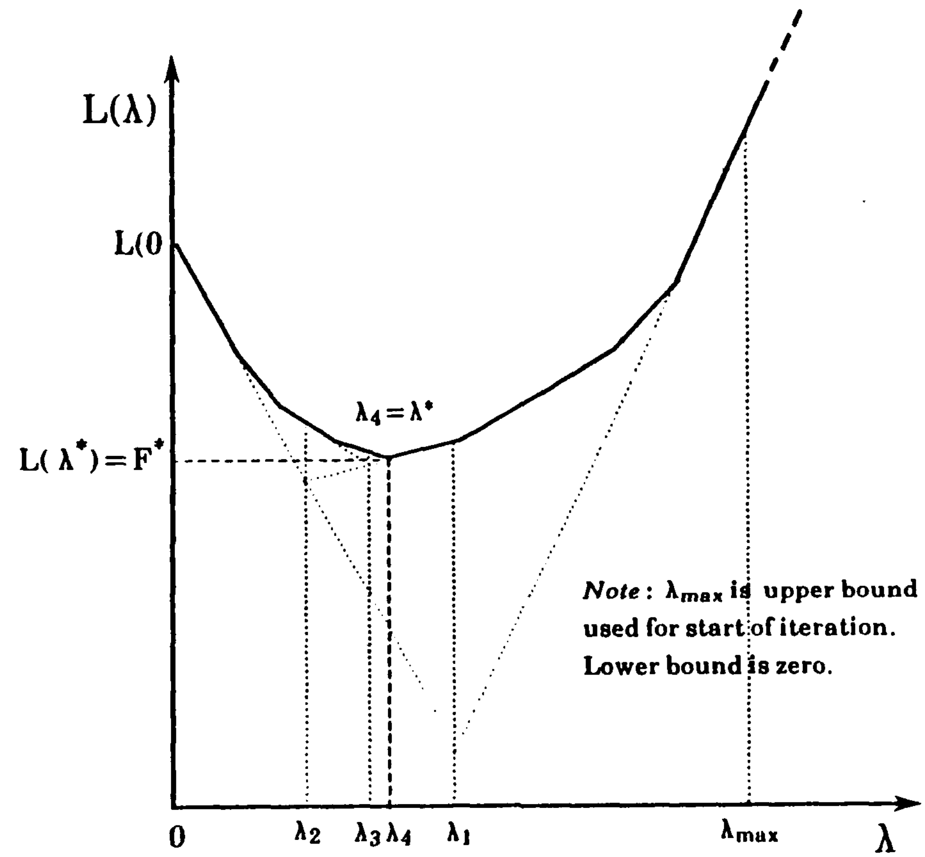


Figure 3.4: Iterations for Derivation of λ^*

effectiveness solution, which is marked 1 in Figure 3.5. The corresponding value of λ^* is obviously zero. The budget is then set to just under the value of the cumulative life-cycle cost C_1 of the maximum effectiveness solution. This produces the next solution point, marked 2 in the diagram, and the process is repeated until we reach the minimum cost solution, which is the sixth solution. No solutions will be obtained for budgets less than C_6. The optimal Lagrangian multiplier λ^* obtained in each case determines the slope of the line segment to the right of the corresponding solution point. It may be noted that the efficiency boundary consists of bounding hyperplanes which envelope the solution space but do not pass through all the

Pareto-efficient points. There are, for instance, three such points denoted by circles for budgets between C_3 and C_4 which will not be discovered by the Lagrangian relaxation method. The basic cause of these inaccessible regions (called *gaps*) is non-concavity in the relationship between the optimal effectiveness and cost. These gaps will not exist if the law of diminishing marginal utility holds strictly. H. Nakayama, et al., [Nakayama, 1975], has a good survey of methods to deal with this characteristic of the Lagrangian relaxation method. The existence of these gaps does not create a problem as far as the application of the method in systems analysis is concerned. This is because the solution offering a maximum overall effectivenss-to-cost ratio is always a Lagrangian solution point. Also, a straightforward application of dynamic programming will produce the minimum cost solution even if it does not lie on the efficiency boundary. Note that as system lives are modeled explicitly for economic, technological and politico-military changes, the net cost of alternatives can be amortized over the proper period to reveal the true minimum cost solution as defined by amortized annual cost, as will be amplified in the following paragraph.

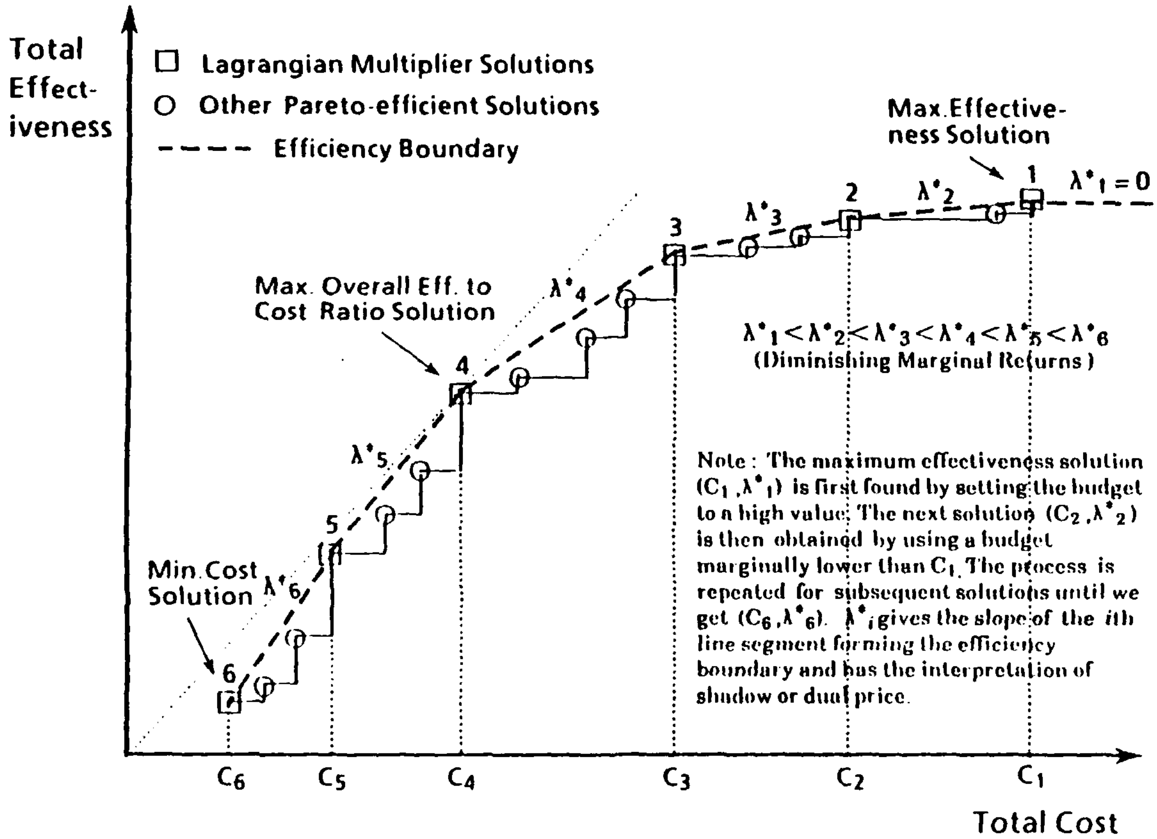


Figure 3.5 : Derivation of Efficiency Boundary by Lagrangian Relaxation Technique

We have seen how characterization of the systems renewal problem as a constrained optimization problem (in which one seeks to maximize effectiveness for a given budget) enables us to obtain the efficiency boundary corresponding to a given scenario. A band of these boundaries is found for each set of scenarios investigated. If probabilities are attached to scenarios, our "expected" efficiency boundary and its associated optimal solutions can be obtained. Furthermore, bearing in mind that the cost of an arc in the network is set to infinity if there is insufficient lead time preceding it or if any performance parameter deteriorates below its requirement level, we know that any solution with finite cost is feasible from the effectiveness point of view. The minimum cost, in current year dollars, for the various feasible solution paths, as well as the associated period of use, can then be translated into amortized costs flows for given interest rate assumptions. On this basis, we can find the solution that allows us to minimize equivalent annual cost while meeting a given set of lead time and performance requirements. Therefore, both the fixed budget and the fixed effectiveness approaches are embodied within the model, delivering the maximum overall effectiveness-to-cost ratio solution and the minimum cost satisficing solution respectively. Furthermore, it should be noted that λ^* has the interpretation of shadow or dual prices in economic analysis. Therefore, efficiency boundaries of systems with similar MOEs can be meaningfully compared. Also, choice of system mix for various capabilities may be guided by the fact that shadow prices should be roughly the same for all the systems in an optimal mix. The combined use of dynamic programming and the Lagrangian relaxation technique thus provide us with a conceptually simple, yet potent and useful methodology that is completely congruent with and derivable from the tenets of systems/economic analysis.

IV. IMPLEMENTATION

A. INTRODUCTION

The dynamic systems renewal planning model (DSRPM) presented in the previous chapter provides a formal basis by which diverse economic, technological and politico-military concerns may be integrated within a common framework (Figure 4.1) to make for more rational management of defense assets. Credible and valid results, however, can be obtained only with the active participation of relevant logistics, engineering, finance, intelligence and operational agencies in the development of proper effectiveness and cost sub-models as well as realistic scenarios. High-level management support is thus essential for the successful implementation of the model. To foster a better understanding of the model and to demonstrate its plausibility and usefulness, a small prototype was developed based on a simple hypothetical weapon system. This prototype is documented in the next chapter along with case-studies. Although the addition of selected successful applications would give greater credence to the model, the limited time available for work on this thesis precluded full-scale implementation for any real systems. Nevertheless, effort shall be made to outline conceptually how implementation is envisaged. Only aspects of cost estimation, effectiveness modelling and requirement formulation peculiar to DSRPM is discussed. For a full discussion, the reader is referred to relevant materials in the bibliography.

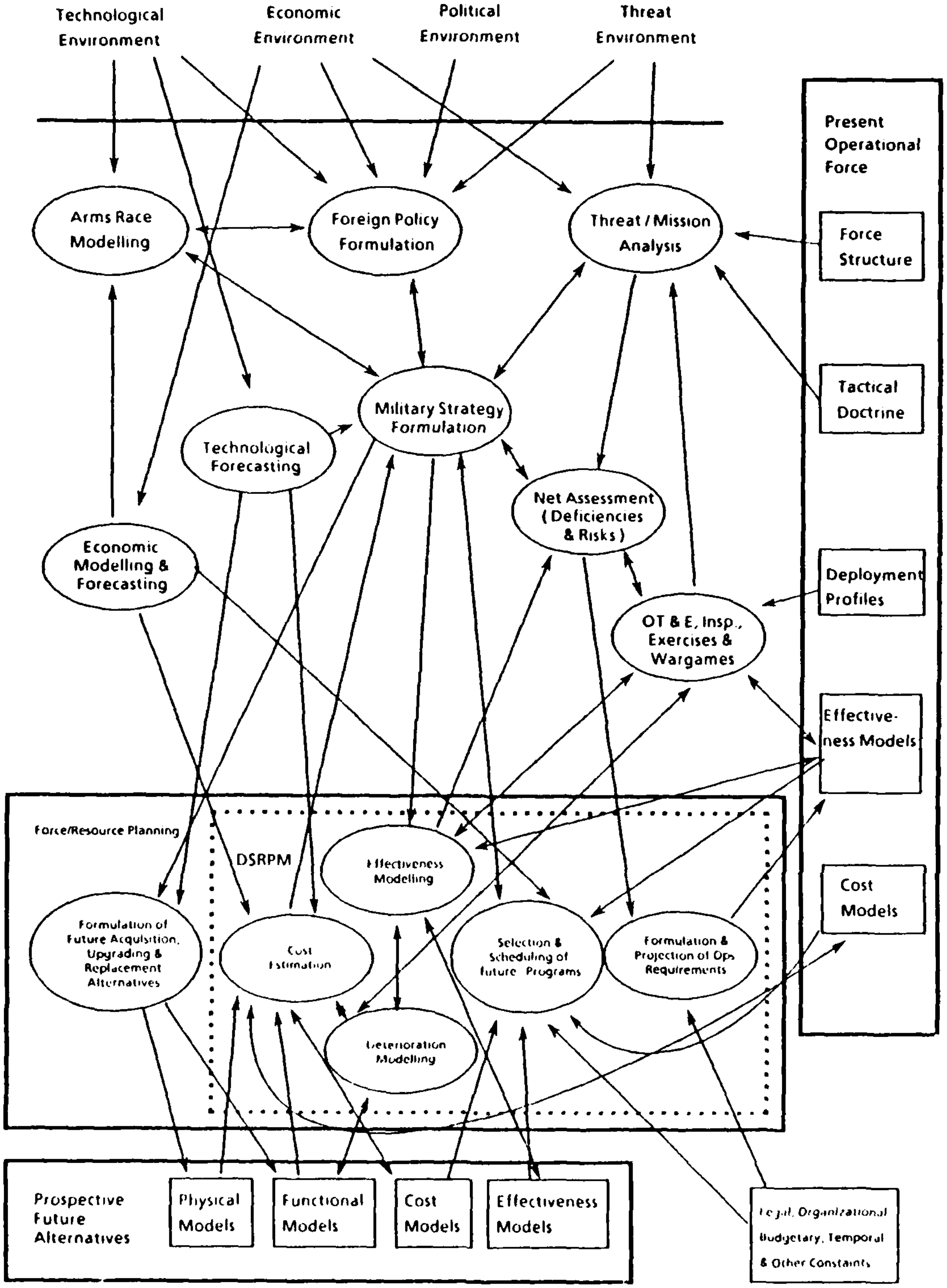


Figure 4.1: System Renewal Planning Framework

B. CONCEPTUAL FRAMEWORK

Implementation of the model is best explained in terms of its constituent elements and their relationships to the processes involved in defense planning. As depicted in Figure 4.1, DSRPM has five elements, all of which are part of the force/resource planning process. A model with these five elements is developed for each entity of force planning, which may be weapon systems, task forces, battle groups, etc. In renewal planning parlance, all these entities are simply called systems, and candidate systems are called alternatives.

The cost estimation element projects the life-cycle costs for both the present system as well as future alternatives. The effectiveness modelling element concerns the appraisal of the value of a system as a function of its measures of effectiveness. The deterioration modelling element accounts for the change in effectiveness and cost over the life of a system caused by wear-out, operational attrition and enemy response. The other two elements are self-explanatory. All of these elements and their implementation are elaborated in sections C, D, and E. Only deterioration modelling and the selection and scheduling of programs are organic to the DSRPM. The other elements are on-going force/resource planning processes adapted with future projections for use in the DSRPM.

Formulation of future alternatives is a part of the force/resource planning process that lies wholly outside the province of the DSRPM. It involves definition of the physical and functional forms of alternatives identified in the strategy formulation process and is shaped by technological outlook. Alternatives encompass the following:

1. Conversion of incumbent systems to serve different roles

2. Upgrading of incumbent systems to serve expanded or higher roles

3. Modernisation of incumbent systems to better serve their assigned roles

4. Replacement of incumbent systems with newer and probably better alternatives

5. Activation of reserve systems for active deployment (incumbent systems are the ones in dormant or preserved status)

6. Reduction of number of incumbent systems through disposal/sale

7. Retirement of incumbent systems into the reserves

8. Acquisition of new (no precedent) systems to meet qualitative and/or quantitative deficiencies or new (threat) requirements.

No present system exists, i.e., system A in the network shown in Figure 3.1 does not exist, in the case of new acquisitions.

C. EFFECTIVENESS MODELING

The effectiveness modeling adopted in the DSRPM is completely congruent with the way military systems are selected and managed. Each system has one or more missions that represent the raison d'etre of that system. These missions are usually phrased in terms that are too broad for concrete guidance. What it takes to carry out the mission(s) are stipulated clearly as required operational (capabilities) requirements. These are usually lower bounds set on key performance parameters such as speed, payload, survivability, operational range, etc. The effectiveness of candidate systems is evaluated based on these key parameters and some criterion. The decision to choose a particular system need not be based exclusively on objective parameters, and the criterion used is not necessarily a formal one. The views

of qualified experts and decision makers are also important. In fact, the political process leading to the decision may even be colored by elements that detract from the military contribution to national security, such as amicable relations with another state. However, assuming rational arguments hold sway, an effectiveness model representing the embodiment of the values, preferences and possibly biases of the decision makers, tempered with experience gained from performance audits, can be constructed. Justification papers, test and evaluation plans, trial reports, etc. are good sources of information needed to construct an effectiveness model. Combat models and wargames also provide valuable input. The aim of effectiveness modelling for this model is to describe value judgements of the decision-makers and not to predict battle outcomes (although predictions do tend to affect judgement). Therefore, the same effectiveness model used for evaluation of alternatives in the acquisition phase, and possibly altered by performance audits during deployment, is incorporated in the DSRPM. The only difference in the DSRPM case is that prospective alternatives are evaluated alongside the incumbent, and performance parameters are projected both for future generations of each alternative as well as through the years of use after an alternative is acquired. Figure 4.2 shows how the j^{th} performance parameter of an alternative as acquired in year y may change over the years of usage t.

As an example, let us suppose that a weapon system was evaluated based on an effectiveness model with the following additive structure:

$$\begin{aligned} TE_a &= \sum_{j=1}^{m} W_j U_j \{X_{j,a}\} \quad \text{provided } X_{j,a} \geq \underline{X}_j \text{ for } \forall j \\ &= 0 \qquad\qquad\qquad\qquad \text{otherwise} \end{aligned} \tag{4.1}$$

where

- TE_a is the total effectiveness of alternative a.

- W_j is the weight of the j^{th} performance parameter expressing its importance relative to the other parameters.

- $X_{j,a}$ is the value of the j^{th} parameter for alternative a.

- $U_j\{X_{j,a}\}$ is the utility function that transforms $X_{j,a}$ into a utility value.

- $\underline{X}_j$ is the minimum level required of the j^{th} parameter (operational requirement).

In this case, the effectiveness sub-model used in the application of DSRPM to the system will be:

$$TE_{a',y}(t) = \sum_{j=1}^{m} W_j U_j \{X_{j,a',y} d_{a',j}(t)\} \tag{4.2}$$

where

- $TE_{a',y(t)}$ is the total effectiveness of alternative a' (not necessarily the same as a) if acquired new in year y during the t^{th} year of deployment.

- $X_{j,a',y}$ is the value of the j^{th} performance parameter for alternative a' if acquired in year y.

- $d_{a,j}(t)$ is the deterioration function for the j^{th} parameter of alternative a' in the t^{th} year of deployment.

The alternatives a and a' need not be the same. The latter typically comprises not only the replacement alternative, but also upgrading options. Note that the structure of the effectiveness model, weights and utility functions are retained in

the DSRPM. $TE_{a',y}(t)$ is the effectiveness associated with all arcs representing alternative a', leading out of nodes of year y, with life-spans of t years in the network shown in Figure 3.1. If $X_{a',j}(t) < \underline{X}_{j,y+t}$ for any j, i.e., if any parameter fails to meet the requirement level stipulated for the year of operation $(y+t)$, then the cost of the corresponding arc is set to infinity.

The effectiveness model used here is similar to that of the TASCOM methodology developed by The Analytic Sciences Corporation for OSD over several years in the late 1970's and the early 1980's. The TASCOM model provides a first-order indication of an aircraft performance potential by computing a score based on attributes such as range, speed, maneuverability, payload, basing mode, target acquisition and fire control capabilities. These factors are normalised against a consistent standard or assigned a graduated evaluation score. The relative weights are based on the consensus judgment of experienced pilots as well as military analysts. The final performance are scores based on weighted calculations. The reader is referred to Hildebrandt, et al., 1986, and Congressional Budget Office, "*Tactical Combat Forces of the USAF, Issues and Alternatives,*" April 1985, for further details on the TASCOM methodology.

The values of the parameters for future versions of each alternative are projected as $X_{j,a',y}$. These are discounted (for deterioration) through the years of usage by the function $d_j(t)$. Technical expertise is required for such forecasting. Requirement levels $\underline{X}_{j,y+t}$ need not be static but may be varied through the future years in accordance with projected threats. Figure 4.2 illustrates how this requirement level may change with time. Projections are required only for the span of the underlying network (Figure 3.1) and a steady state should be assumed beyond the forecast horizon. These projections form the effectiveness aspect of DSRPM scenarios. Examples of $U_j\{\ \}$ and $d_{a',j}(\ )$ are shown in Figures 4.3 and 4.4 respectively.

The utility function $U_j\{\ \}$ is the instrument that allows us to express non-linear relationships such as that of diminishing marginal utility. Adjusting it regularly for the effect of changes in enemy force structure, size, tactics, strategy, etc., also serves to account for the interactive nature of defense "posturing". The example shown here is of explicit utility functions and single mission systems. Implicit approaches may be used if utility functions can be specified explicitly only with considerable difficulty. Multiple mission systems may be modelled by combining utility values using weights or other multi-criteria modelling schemes.

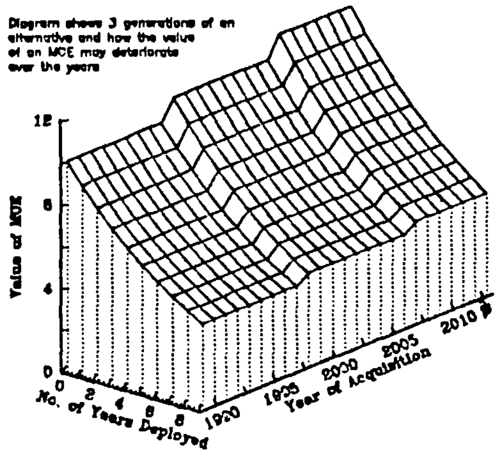


Figure 4.2 a : Change in MOE Value

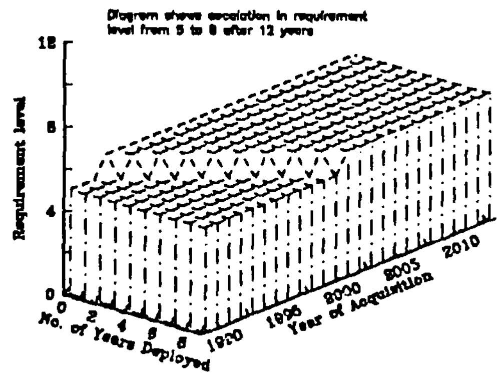


Figure 4.2 b : Change in Requirement Level

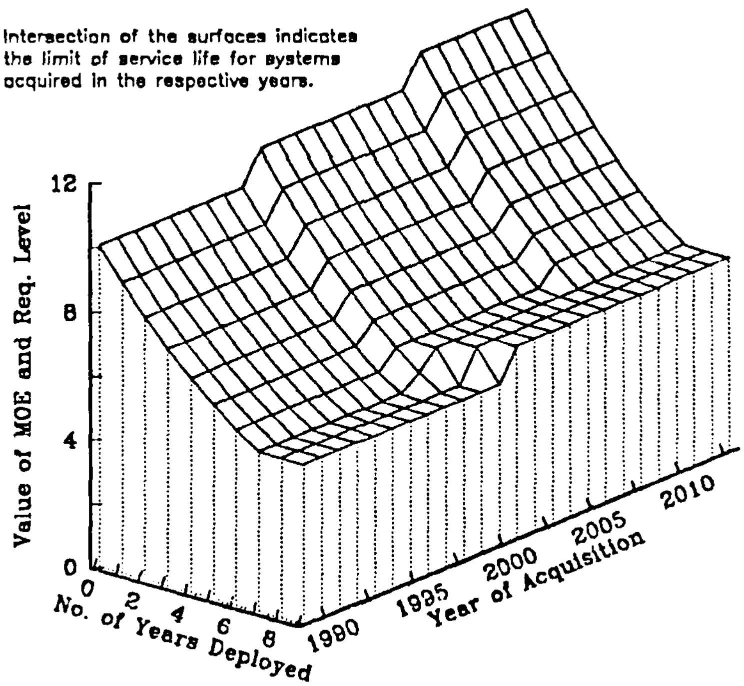


Figure 4.2 c : Change in MOE Value and Requirement Level

Figure 4.2 : Illustration of Change in MOE Value and Requirement Level

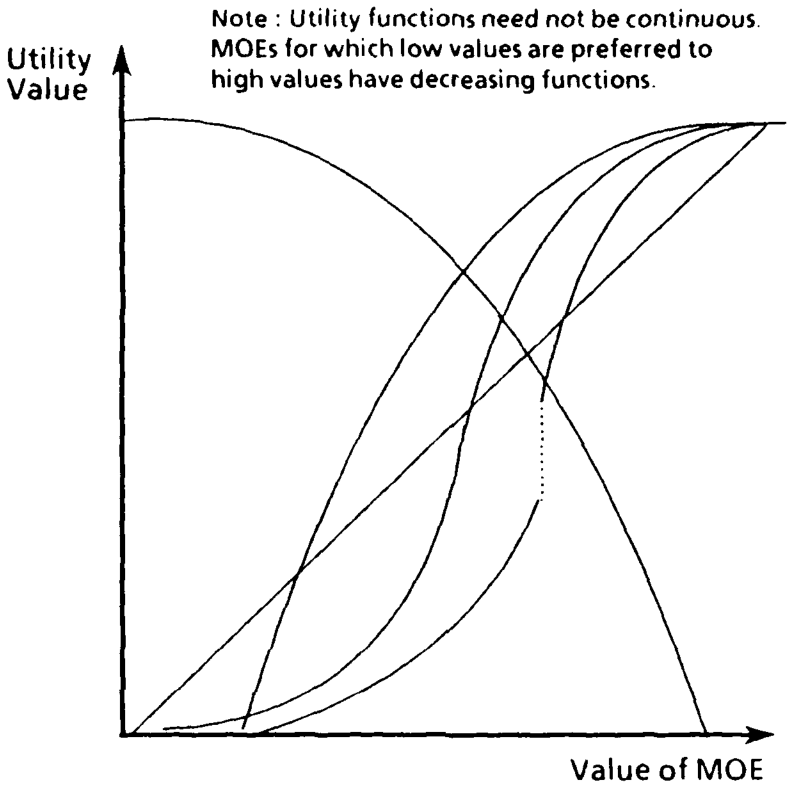


Figure 4.3 : Examples of Utility Functions

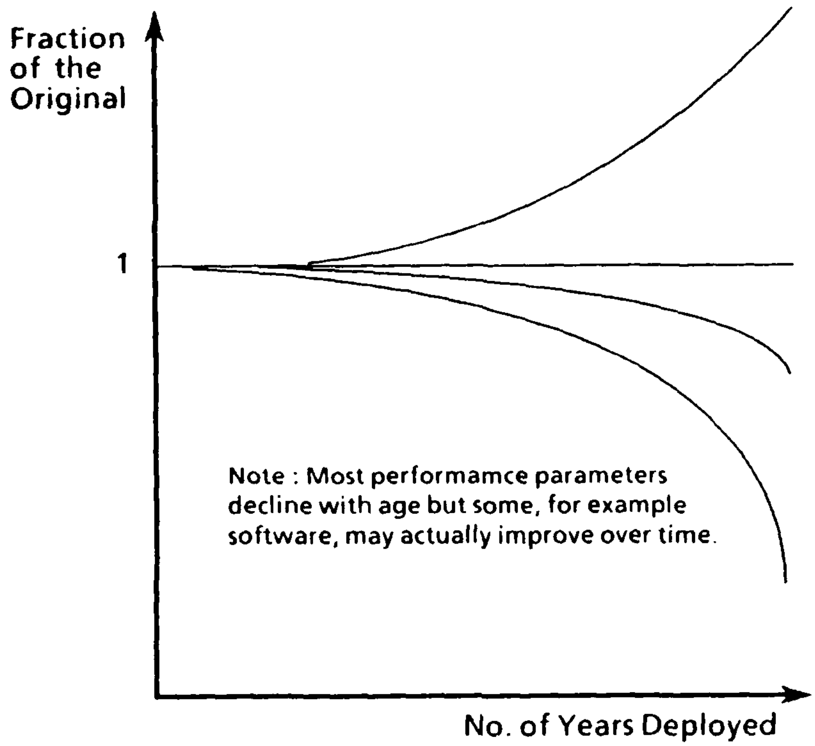


Figure 4.4: Examples of Deterioration Functions

D. COST ESTIMATION

Resource requirements are evaluated for both incumbent systems and prospective alternatives. Cost models for the former deal with the projection of ownership costs based on actual cost experience as well as forecasts of disposal cost or salvage value. Those models developed for future alternatives are either statistical ones based on the physical and functional characteristics of these alternatives (Figure

4.1) or analogy types based on comparison of similar systems and judgement concerning complexity factors. Procurement costs are included in cost estimation of alternatives but are considered sunk costs in the case of incumbent systems.

Cost models used in DSRPM differ from the ones typically used in evaluations in that various types of costs such as procurement cost, operating cost, etc., are estimated not just for one possible life-cycle but for multiple possible ones in the future. The projection of costs needed to adapt cost models for use in DSRPM is usually accomplished using time-series or regression analysis. Adjustments may be made if significant and relevant technological breakthroughs are anticipated. For example, if major advances in certain automation technologies are expected five years from now, then manpower costs may be adjusted accordingly. Such adjustments should be made conservatively and in a not too abrupt manner. Figure 4.5 shows an example of the cost parameter forecasts that are used in the model.

To examine how costs may be projected into the future, let us consider the following simplified li cycle cost model:

$$LCC_{a,y}(t) = AC_{a,y} + MC_{a,y}t^{\gamma_{a,y}} + OC_{a,y}e^{\delta_{a,y}(t-1)} + DC_{a,y}(t) \tag{4.3}$$

$$DC_{a,y}(t) = U_{a,y} - V_{a,y}e^{-\eta_{a,y}t} \tag{4.4}$$

where:

- $LCC_{a,y}(t)$ is the life-cycle cost of alternative a if procured in year y and used for t years
- $AC_{a,y}$ is the acquisition cost of alternative a if procured in year y
- $MC_{a,y}$ is the maintenance cost of alternative a in the first year if procured in year y

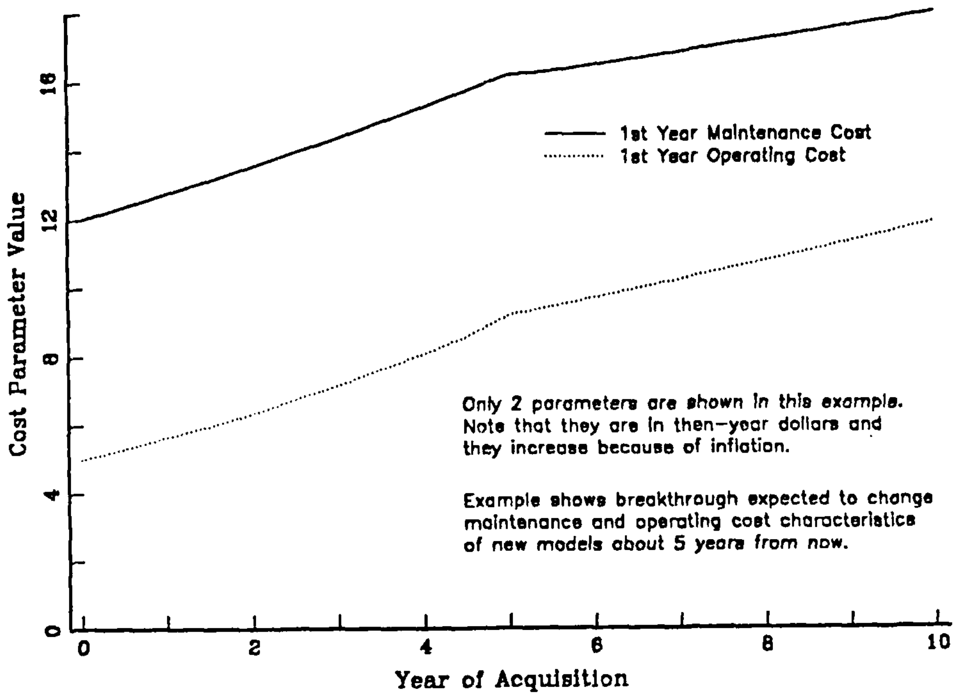


Figure 4.5: Examples of Cost Parameter Forecast

- $OC_{a,y}$ is the operating cost of alternative a in the first year if procured in year y

- $DC_{a,y}(t)$ is the disposal cost of alternative a if procured in year y and used for t years (Note: This may be negative if asset has resale value.)

- $U_{a,y}$ is the upper bound of $DC_{a,y}(t)$

- $V_{a,y}$ is a proportionality constant dictated by the resale market

- $\gamma_{a,y}, \delta_{a,y}$ and $\eta_{a,y}$ are exponential constants

If inflation and technological change have been (and presumably will be) gradual, the individual costs may be forecasted using non-linear regression models such as the following:

$$AC_{a,y} = PAC_a(1 + r_{AC})^y + e_y \tag{4.5}$$

where:

- PAC_a is the present acquisition cost of alternative a
- r_{AC} is the compound inflation-technological improvement rate for acquisition cost
- e_y is the error term

Solutions are obtained using either the maximum likelihood approach or Zellner's method [Judge, et al., 1988] based on historical data. If major breakthroughs are expected in the production of alternative a, the forecasted figures for $AC_{a,y}$ may be adjusted to some extent. Anticipated foreign exchange rates may also be factored into cost projections if they are relevant to a system renewal problem. The cost aspect of DSRPM is manifested in these projections. There are many different methods of forecasting both cost and effectiveness [Ayres, 1969, Stewart and Wyskida, 1987, and Ascher and Overhold, 1988], the choice of which depends very much on the degree of understanding one has of the dynamics of the change process.

E. OTHER ELEMENTS

The deterioration function $d_j(t)$ introduced in the section on effectiveness modelling is an example of how the change in performance parameters over the life of a system may be modelled. Audit programs such as OT&E, inspections and exercises as well as technical trials and laboratory tests provide the data needed to derive these functions. To see how deterioration may be incorporated in a cost model, let

us consider the following maintenance cost model:

$$\frac{dM}{dt} = cM^{\alpha}t^{\beta} \tag{4.6}$$

where:

- M is the cumulative maintenance cost incurred
- t is the age of the system
- c is a proportionality constant
- α and β are exponentiality constants

This model links the rate of change in maintenance cost to the age t as well as past maintenance effort measured in terms of cumulative cost. Given an initial condition of $M = 0$ at $t = 0$, we have:

$$M = At^{\gamma} \tag{4.7}$$

where:

$$\gamma = \frac{1+\beta}{(1-\alpha)} \tag{4.8}$$

$$A = \left[\frac{c}{\gamma}\right]^{\frac{1}{1-\alpha}} \tag{4.9}$$

$$\alpha \neq 1 \tag{4.10}$$

Hence the rate of increase in maintenance cost is given by:

$$\frac{dM}{dt} = A\gamma t^{\gamma-1} \tag{4.11}$$

The parameters A and γ are obtained by using regression analysis on historical maintenance cost date. A is the maintenance cost incurred in the first year of use.

As γ is always greater than 1, the rate of increase in maintenance cost $\frac{dM}{dt}$ will always be increasing over time. The impact of inflation and technological advances in maintenance cost is modelled by varying both A and γ for future alternatives. A reduction in operating cost for future generations may also be modelled in a similar fashion.

Operational requirements for present systems are projected by defining the minimum requirement level in each year for various performance parameters of a system. These are denoted as $\underline{X}_{j,y+t}$ in section B. For instance, shifts in enemy beach defence tactics may result in significant increases in the speed required of amphibious assault craft. Requirement projections form an integral part of a DSRPM scenario and are driven mainly by the net assessment process (Figure 4.1).

Force levels decline even in peacetime with attrition due to accidents, wear and, in the case of human systems, retirement and resignation. If the number of an alternative a' acquired in year y is taken to be the performance parameter $X_{j,a',y}$, the decline due to attrition can be modelled by the deterioration function $d_{a,j}(t)$. The effectiveness of various force levels can then be modelled using the associated utility function $U_j\{\}$, and the force level requirement in the year $(y+t)$ is simply $\underline{X}_{j,y+t}$. Treating the number acquired as a performance parameter in this way allows us to check the adequacy of the size of an acquisition. The attractiveness of a phased build-up versus the economies of a bulk buy may be studied by defining alternatives representing different systems and force levels. DSRPM produces an acquisition program that meets projected force level requirements by selecting and scheduling these alternatives. Figure 4.6 illustrates the kind of solution that may be generated by DSRPM in such studies. Force mix can be optimised by ensuring that the lagrangian multiplier associated with the levels of the various force components are similar. In this way, force level and mix issues can be dealt with by the model.

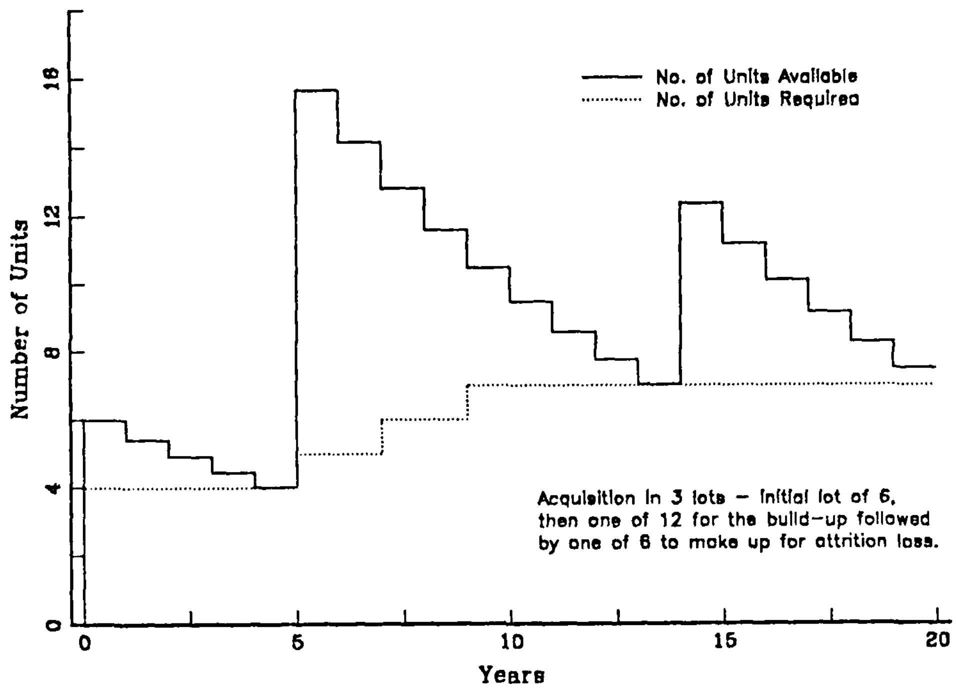


Figure 4.6: Phased Acquisition Solution Example

The last element we look at concerns the selection and scheduling of alternatives for implementation. The inputs for these are the cost and effectiveness models discussed in sections B and C of this chapter as well as budgetary, temporal, legal and other constraints. The combined dynamic programming – Lagrangian relaxation discussed in Chapter 3 is applied to these inputs to produce solutions for the fixed budget and fixed effectiveness approaches. Constraints in the form of quantitative rules can be incorporated within DSRPM. An example is that of lead time requirements for various alternatives which is implemented in the prototype that was developed. The model is exercised by iterating it for various scenarios to make

explicit uncertainties faced by the decision maker. Strategic considerations with the formal quantitative results from DSRPM are then the basis of system renewal decisions which are the output of the force/resource planning process.

DSRPM is easily implemented in phases. The model could first be applied to a couple of incumbent systems for which systems renewal decisions are expected in the next one or two years. This would allow enough time for a full implementation of the model for these systems. This phase serves to validate the model with a real application and the experience gained would guide implementation in the next phase. The model should however be applied as early as possible in a system's life-cycle to provide enough time for the cost and effectiveness models to be refined with inputs from operational trials, exercises, wargames, etc. Therefore, the second phase should see the model applied to some new acquisitions. When management is comfortable with the model and is ready to introduce it on a broader scale, a master implementation plan can then be formulated to formalise the use of the model.

V. PROTOTYPE DESIGN

A. GENERAL

To foster a better understanding of the DSRPM, a prototype was developed based on a hypothetical weapon system. This chapter documents the prototype which was developed on an IBM AT-compatible personal computer using PC SIMSCRIPT II.5. The language was chosen for its superlative power and ease of use, as well as its provisions for incorporation of simulation in later development. The program is designed to produce for each run a single solution path corresponding to a point on Figure 3.2. The program reads data from an input file "IN.DAT" and channels results to an output file "OUT.DAT". The type of solution depends on the approach selected for that run, namely Lagrangian relaxation, maximum effectiveness, minimum satisficing cost or maximum system cost effectiveness ratio. Solution approach is specified by the user in the input file. The budget is relevant only when the Lagrangian method is used. The overall structure of the prototype is described in Figure 5.1 and the program is listed in Appendix A.

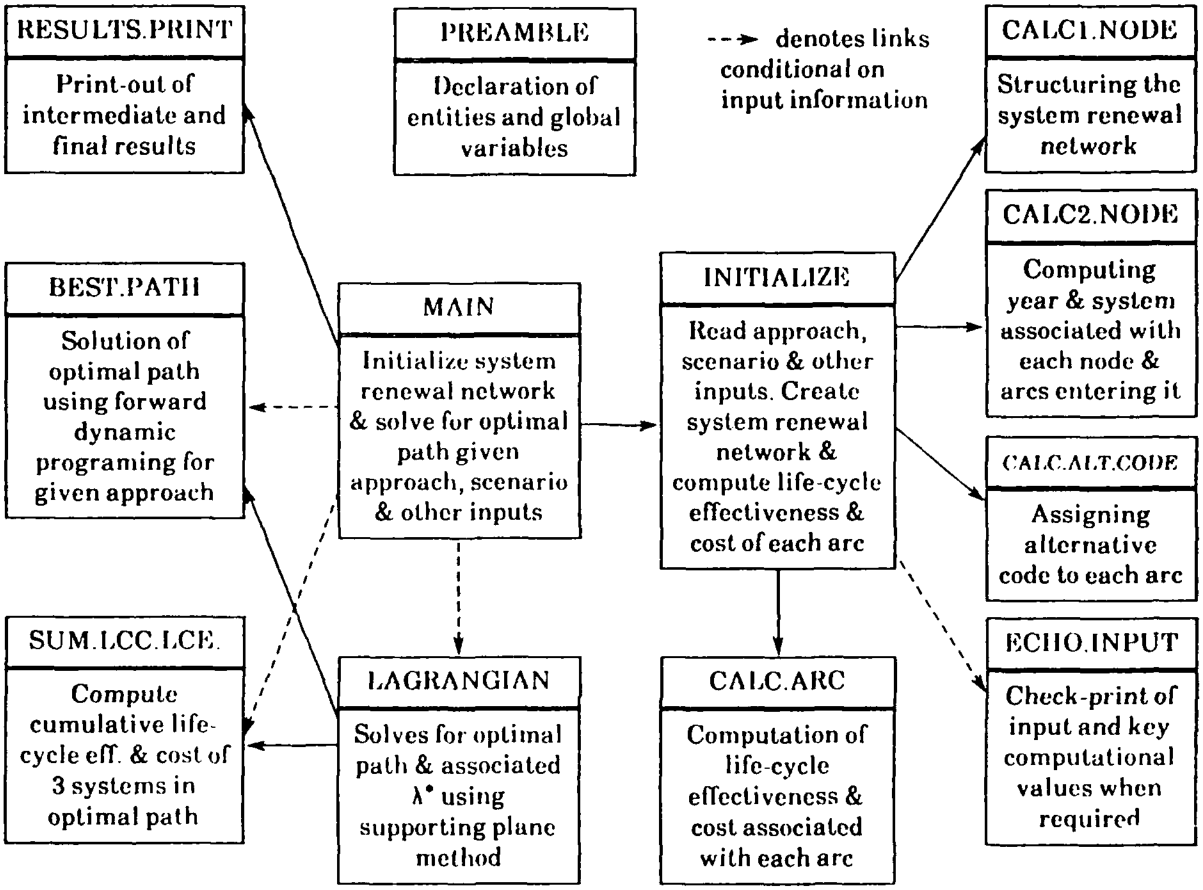


Figure 5.1 : Prototype DSRPM Block Diagram

B. ASSUMPTIONS

The following assumptions are peculiar to the hypothetical weapon system upon which the prototype was developed:

- The effectiveness sub-model is given by Equation 4.3 which was discussed as an example in the previous chapter. Deterioration functions $d_{a,j}(t)$ are assumed to be exponential for all a and j. Furthermore, utility functions $U_j\{X\}$ are assumed to be linear and bounded (maximum value of 1) as follows:

$$U_j\{X\} = \frac{X}{max\{X\}} \tag{5.1}$$

Therefore, the total effectiveness of an alternative a acquired in year y in the t^{th} year of use is given by:

$$\begin{aligned} TE_{a,y}(t) &= \sum_{j=1}^{n} W_j U_j \{X_{j,a,y} d_{a,y}(t)\} \qquad (5.2) \\ &= \sum_{j=1}^{n} \frac{W_j X_{j,a,y}}{\max\limits_{a,y}\{X_{j,a,y}\}} e^{\rho_{j,a,y}(t)} \end{aligned}$$

- The cost sub-model used is also similar to the example discussed in the previous chapter. Annual maintenance cost $AMC_{a,j}(t)$ is assumed to be:

$$AMC_{a,y}(t) = K_{a,y}\gamma_{a,y}t^{\gamma_{a,y}-1} \tag{5.3}$$

At the end of a system's life, all parts that can be salvaged are sold and those parts that could not be sold are disposed of at a certain cost. Therefore, the model has both disposal cost and salvage value. Operating cost, disposal cost and salvage value are all assumed to vary exponentially through the years.

Therefore, the total life-cycle cost incurred by an alternative a acquired in year y and used for t years is:

$$
\begin{aligned}
LCC_{a,y}(t) &= AC_{a,y} + DC_{a,y}e^{\eta_{a,y}t} + SV_{a,y}e^{\sigma_{a,y}t} \\
&\quad + \sum_{t=1}^{n}\left\{K_{a,y}\gamma_{a,y}t^{\gamma_{a,y}-1} + OC_{a,y}e^{\delta_{a,y}t}\right\}
\end{aligned}
\tag{5.4}
$$

C. MODULES

This section briefly explains the function and workings of each component module of the prototype.

1. PREAMBLE

This module is peculiar to the SIMSCRIPT II.5 language. It provides for declaration of entities and global variables. Entities are structured data items that represent elements of a model. Definition of an element as a permanent entity entails the automatic creation of separate arrays for each declared attribute when the entity is created, the length of these arrays being the number of that element. For example, alternatives were defined to be the permanent entity ALT with attributes ALT.NAME and LEAD.TIME. When the entity ALT is created, two arrays with the names of the attributes will be created simultaneously and their length would be equal to the number of alternatives N.ALT (a system variable). Temporary entities would be relevant only in the modeling of dynamic systems where elements enter and leave.

2. MAIN

As the name suggests, this module controls the overall computational flow, which is shown graphically in Figure 5.2. Note that the modules BEST.PATH

and SUM.LCC.LCE are executed several times if the Lagrangian relaxation approach is selected.

3. INITIALIZE

This module reads the input data, controls the modules generating the system renewal network and creates the permanent entities and associated arrays. It also reserves the memory space needed by the arrays. The flowchart for this module is shown in Figure 5.3. The input data is read in free format in the order shown in the listing.

4. CALC1.NODE

The structure of the network is determined in this module based on the number of alternatives and the minimum and maximum life-span of each system. The number of permanent entities NODE and ARC to be created is also computed.

5. CALC2.NODE

This module computes for each node information such as the year and system (transition) it belongs to, as well as the arcs entering it. The hierarchical list data structure illustrated in Figure 5.4 was used to represent the network. Therefore, the indices of the arcs entering node n runs from $EP(n)$ to $[EP(n+1)-1]$.

6. CALC.ALT.CODE

The code of the alternative represented by each arc is assigned in this module.

7. CALC.ARC

This module determines the tail node, life-cycle cost and effectiveness associated with each arc. The one-time cost items in Equation 5.4 are discounted and summed separately from the cumulative items such as maintenance and operating costs. Acquisition cost of the present system is ignored as sunk cost. The benefit

accrued in each year is added to yield the cumulative or life-cycle effectiveness of the arc representing a given alternative and life-span. If the value of any MOE falls below that required in any year spanned by an arc, the life-cycle cost of that arc is set to an unfavorably high value to mark it as infeasible and to prevent its inclusion in the selection path. The highest index of the MOE(s) that failed to meet its requirement(s) is recorded as the limiting MOE in such cases. The flowchart for this module is shown in Figure 5.5.

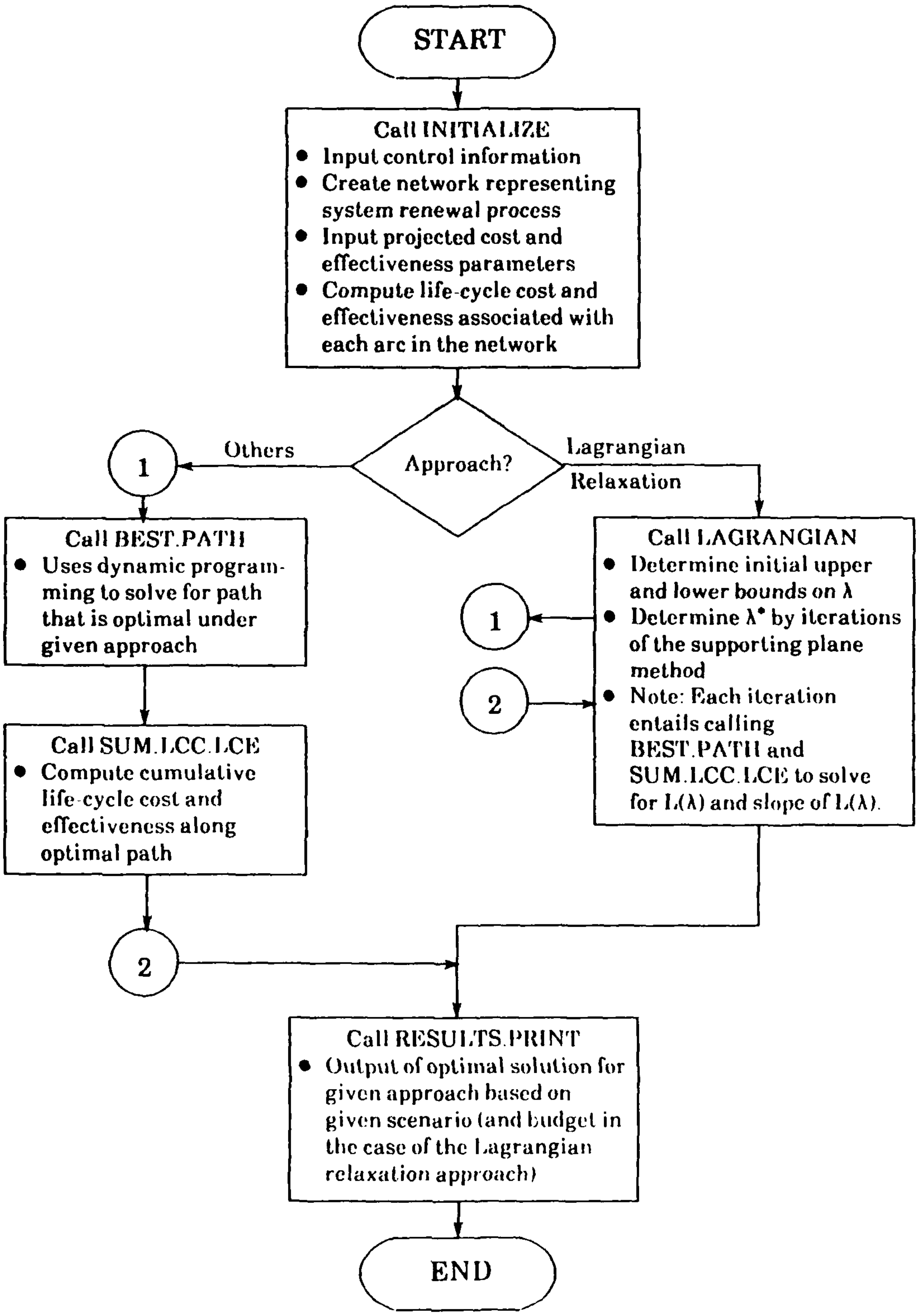


Figure 5-2: Flowchart or MAIN Program

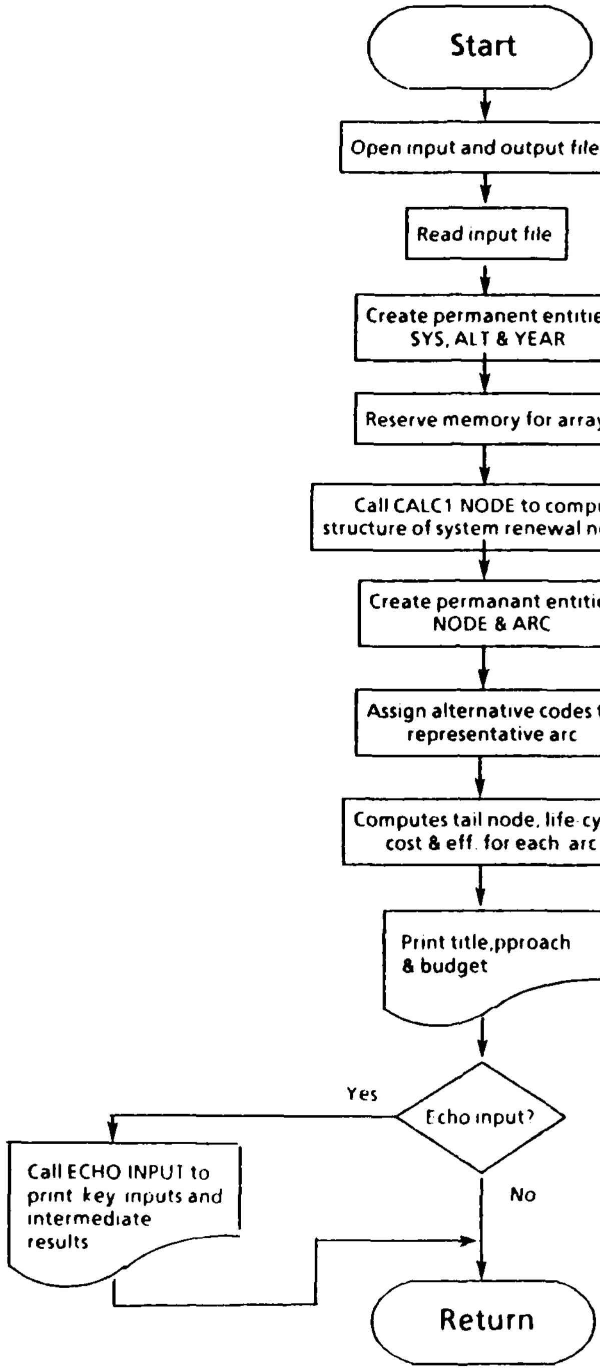
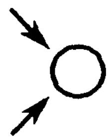


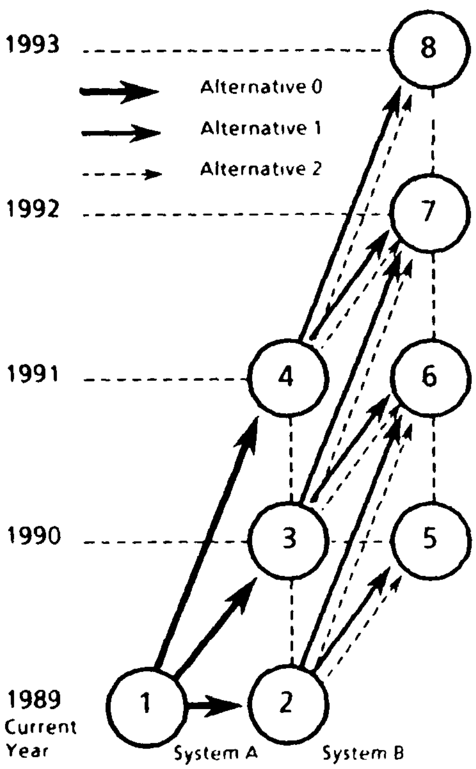
Figure 5.3: Flowchart for INITIALIZE Module

TRANS.YEAR: Transition year
SYS.CODE: Preceding system code
EP: Entry point
TAIL: Tail node
ALT.CODE: Alternative represented

Note: The convention shown here is that of reverse star.



Network Represented



NODE

	Trans Year	Sys. Code
1	1989	0
2	1989	A
3	1990	A
4	1991	A
5	1990	B
6	1991	B
7	1992	B
8	1993	B

Hierarchical List Data Structure

EP
0
1
2
3
4
6
10
14
16

ARC

	Tail	Alt. Code
1	1	0
2	1	0
3	1	0
4	2	1
5	2	2
6	2	1
7	2	2
8	3	1
9	3	2
10	3	1
11	3	2
12	4	1
13	4	2
14	4	1
15	4	2

Figure 5.4: Hierarchical List Data Structure for System Renewal Network

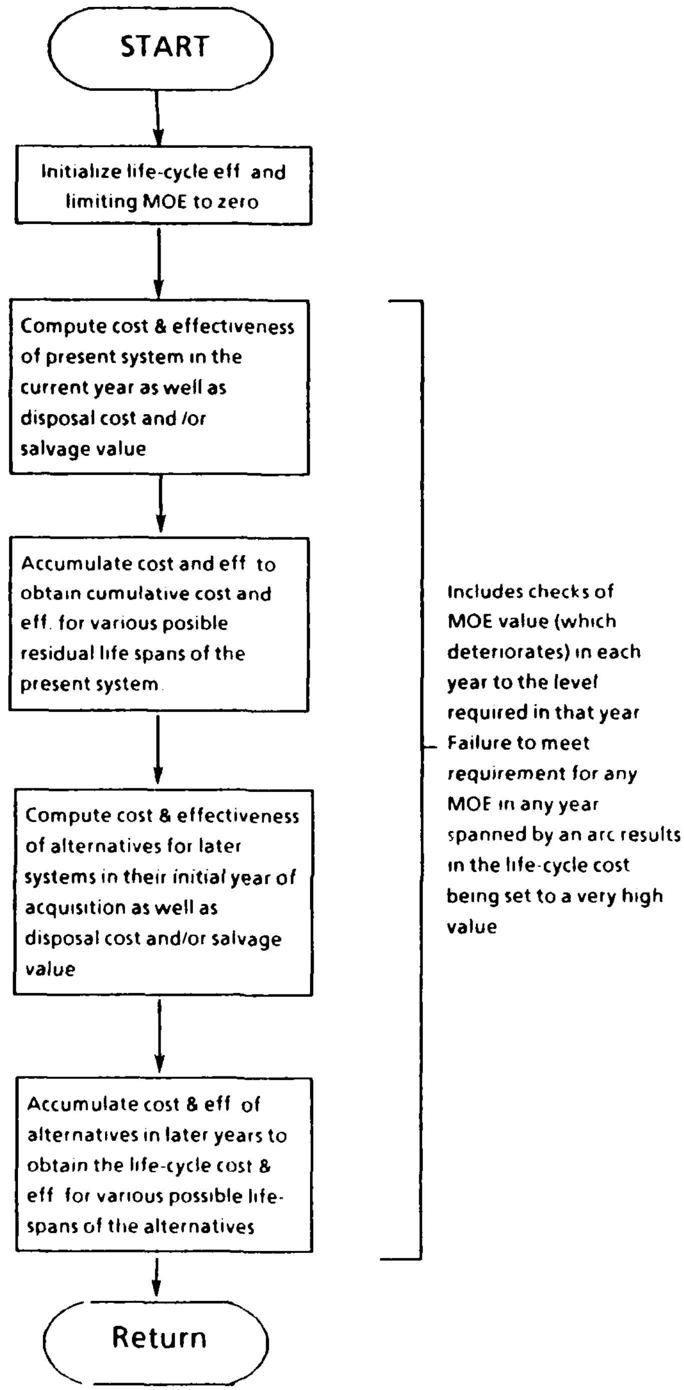


Figure 5.5: Flowchart for CALC.ARC Module

8. ECHO.INPUT

Key inputs may be echoed for debugging purposes by setting the flag variable ECHO.ON in the input file to "on". This module will then be activated and intermediate results such as the life-cycle cost and effectiveness associated with each arc are printed along with the key input data.

9. LAGRANGIAN

This module produces the optimal path for a given budget using the Lagrangian relaxation method. The value of λ^* corresponding to the optimal path is found by iterations of the supporting plane method. Each of these iterations entails calling the modules BEST.PATH and SUM.LCC.LCE to solve for $L(\lambda_i)$ and the slope of $L(\lambda)$ at λ_i. The limitations of binary representation will be exceeded, even with double precision variables, if λ_i and/or the cost values are too high. The initial upper bound λ_{max} given by Equation 3.18 works well for cost values scaled to no more than 10^6. Figure 5.6 shows the flow of the computations in this module. Note that even though the slope at the minimum of $L(\lambda)$ itself may be positive or negative depending on whether $\lambda_3 = \lambda_2$ or $\lambda_3 = \lambda_1$ respectively, the optimal solution path is given by the positively sloped line segment that is adjacent to the minimum point. When $\lambda_3 = \lambda_1$, this line segment corresponds to λ_2 (otherwise, the intercept of the line segments at λ_1 and λ_2 would not have yielded $\lambda_3 = \lambda_1$). Therefore, the slope is readjusted when $\lambda_3 = \lambda_1$.

10. BEST.PATH

This module produces the optimal solution path for the specified approach using forward dynamic programming. The criterion function $L(J)$ associated with each arc J when the approach is to maximize the effectiveness to cost ratio of the individual systems is given by:

$$L(J) = \frac{LCE(J)}{(LCC(J) - MIN.LCC + 1)} \tag{5.5}$$

where:

- $LCC(J)$ and $LCE(J)$ are the life-cycle cost and effectiveness respectively of arc J

- MIN.LCC = $\min_J$ LCC(J)

This is to allow for the possibility of $LCC(J)$ being zero or negative. Provisions are also made to ensure that the solution path has sufficient lead time for each alternative chosen. The computational flow is illustrated in Figure 5.7.

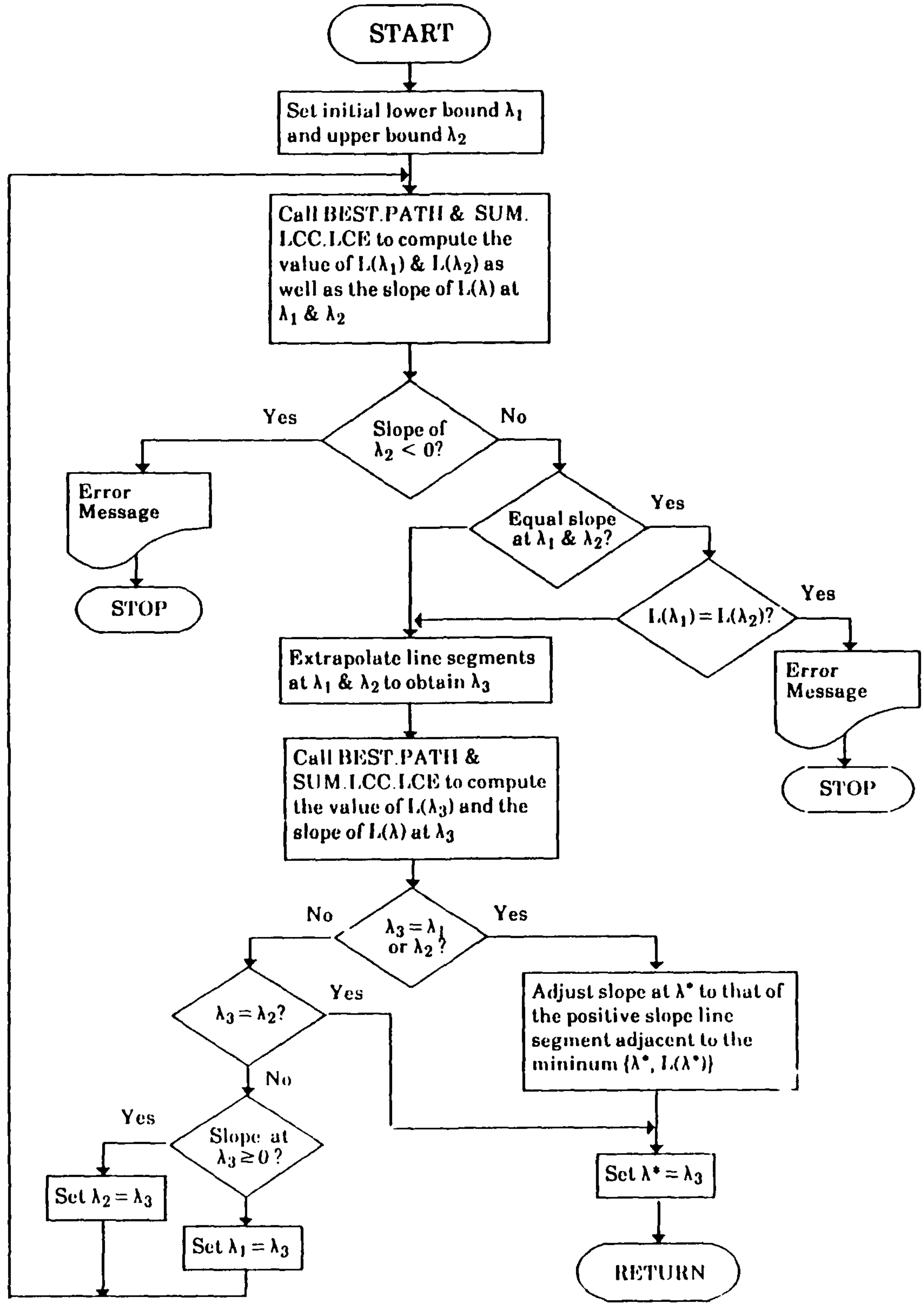


Figure 5-6: Flowchart for LAGRANGIAN Module

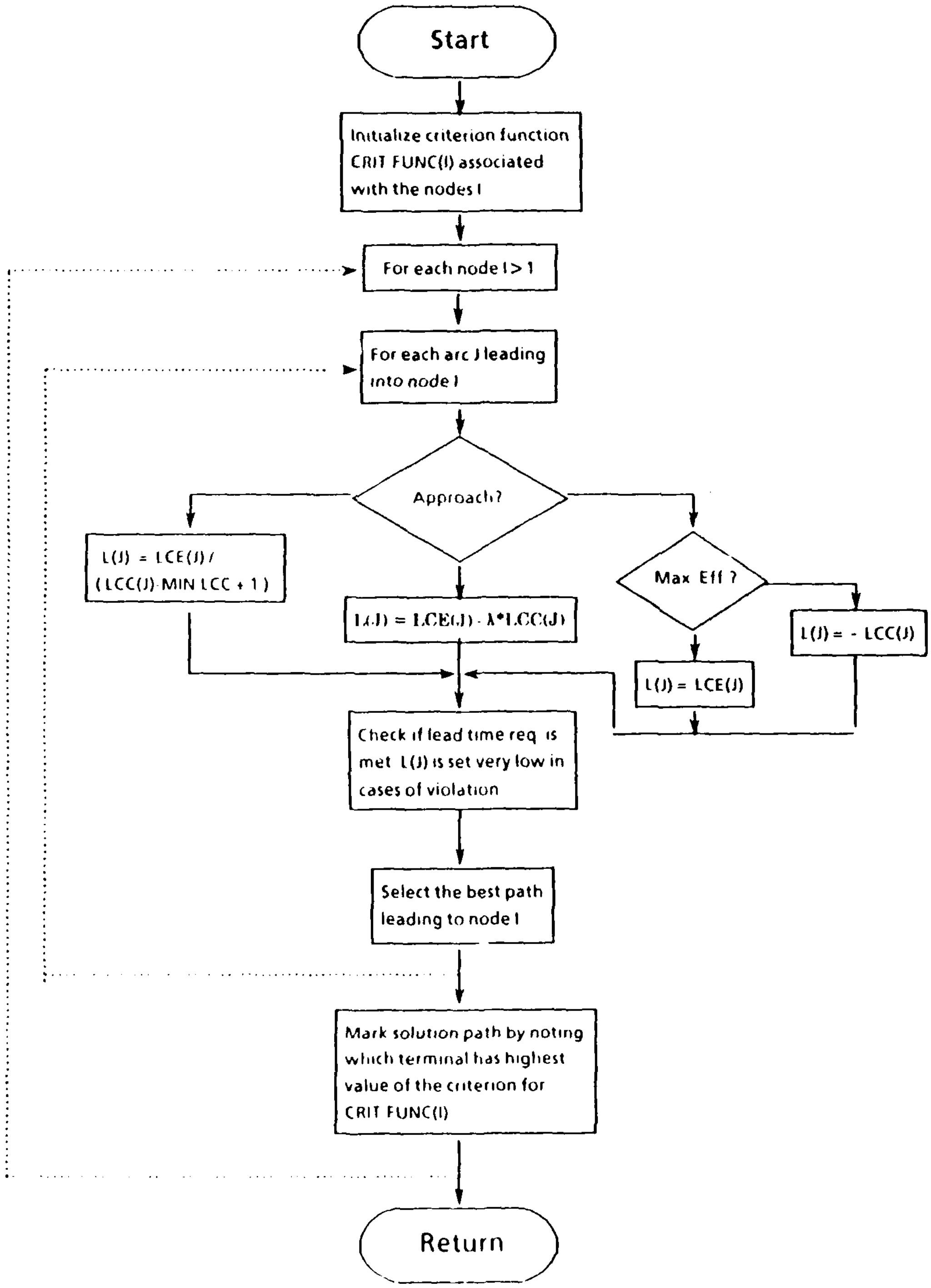


Figure 5.7: Flowchart for BEST.PATH Module

11. SUM.LCC.LCE

The solution path is traced backward from the terminal node with the highest value of the criterior function CRIT.FUNC(I) and the life-cycle cost and effectiveness of the systems are summed along the way in this module. Note that all the terminal nodes will have very low values (negative) of CRIT.FUNC(I) if all paths violate either lead time or MOE requirements or both, i.e., no feasible solution exists. Conversely, if CRIT.FUNC(I) of a terminal node is not a very low value, below 10^{-6}, then a feasible solution path exists that leads to that node.

12. RESULTS.PRINT

Computational results are printed by this module.

D. COMPLEXITY AND EXECUTION TIME

In terms of time complexity, the dominating piece of code is the CALC.ARC module. Let the difference between the maximum and minimum life-span of the present system be n_1 and that of successor systems be $n_2, n_3, \cdots, n_s$, where s is the number of stages or systems in the systems renewal network. If we assume $n - n_i$ for $\forall i > 1$, then the structure of the network is given by Table 5.1.

The total number of arcs n is thus given by:

$$\begin{aligned} n &= 1 + n_1 + a(s-1)(1+n_1)(1+n) + an(1+n)\sum_{i=1}^{s-2} i \\ &= 1 + n_1 + a(s-1)(1+n_1)(1+n) + an(1+n)(s-2)(s-1)/2 \qquad (5.6) \end{aligned}$$

If we let the average life of successor systems be denoted as l, and the number of MOEs evaluated be e, then the growth rate of execution time, ET, is of the order $m(l+e)$. In other words,

TABLE 5.1: System Renewal Network Structure ($n_1 = n$ for $\forall_i > 1$)

Transition #	System #i	No. of Nodes	No. of Arcs
0		1	
	1		$(1 + n_1)$
1		$(1 + n_1)$	
	2		$a(1 + n_1)(1 + n)$
2		$(1 + n_1 + n)$	
	3		$a(1 + n_1 + n)(1 + n)$
3		$(1 + n_1 + 2n)$	
	4		$a(1 + n_1 + 2n)(1 + n)$
4		$(1 + n_1 + 3n)$	
And so on until $i = s$			

Note: a denotes the number of alternatives evaluated

$$
\begin{aligned}
ET &= O\left[m(l+e)\right] \\
&= O\left[\left\{1 + n_1 + a(s-1)(1+n_1)(1+n) + \frac{an^2(s-2)(s-1)}{2}\right\}(l+e)\right] \\
&= O\left[\max(an, ns, an^2s^2)\max(l,e)\right] \qquad (5.7)
\end{aligned}
$$

Therefore, execution time for the prototype DSRPM is of polynomial order, the key determinants of which are n and s. We can also see that time complexity is linear in a, n, l and e. For a run with $a = 2, n_1 = 5, n = 5, s = 3, l = 7.5$ and $e = 3$, the execution time of the prototype DSRPM on the Zenith AT-compatible is typically about 43 seconds.

VI. CASE STUDIES

Case studies were conducted using the prototype to demonstrate the plausibility and usefulness of the DSRPM. To better serve the purposes of illustration and plausibility testing, the case studies were designed to comprise a series of scenarios of incremental complexity, all of which are based on the same hypothetical system discussed in Chapter V. Although effort was made to incorporate as much realism as possible, the case studies and the weapon system were kept simple to better portray the workings of the model. A good understanding of and confidence in the model is necessary before one confronts the complexities involved in a real application.

In the case studies, the key effectiveness parameters or MOEs are assumed to be range (nautical miles), accuracy (percentage hit) and availability (percentage) with relative weight W_j of 0.4, 0.3 and 0.3 respectively. The cost and effectiveness characteristics of the incumbent system assumed are shown in Table 6.1. Disposal cost is assumed to be zero for the incumbent system and alternatives, i.e., $DC_{a,y} = 0$ for $\forall_a$.

TABLE 6.1: Characteristics of the Incumbent System

MOE	Current Value	ρ_0	Cost Parameters					
Range (NM)	104.6	-0.03	Maintenance		Operating		Salvage	
Accuracy (%)	87.2	-0.02	k_0	γ_0	OC_0	δ_0	SV_0	σ_0
Availability (%)	93.5	-0.03	30	1.3	7	0.05	-20	-0.2

As a starting point, we shall assume that two alternatives, 1 and 2, are available and that their minimum and maximum life are five years and ten years respectively. They are assumed to require no development or acquisition lead time (presumably available "off-the-shelf"). The incumbent system (alternative 0) is assumed to have a minimum and maximum life of zero years and five years respectively, i.e., alternatives may be introduced immediately, or at the latest, five years hence.

Four solution approaches are used in each of the case studies, namely the minimum average annual cost (MAAC) approach, the minimum annualised cost (MAC) approach, the system effectiveness to cost ratio (SECR) approach and the Lagrangian relaxation (LR) approach. The average annual cost is obtained by dividing the total cost of a succession of three systems (in current dollars) by the years spanned by the systems. The MAAC approach thus ignores monetary interest. The MAC solution is obtained by amortizing the total cost of the system over the years spanned. It is the solution obtained when one wishes to minimise cost needed to meet effectiveness requirements. The SECR approach maximizes the cumulative total of the effectiveness-to-cost ratio of each of the three systems in a path. The LR approach was explained in Chapter 3. Solution points obtained using the LR approach are linked as in Figure 3.5 to form the efficiency boundary. The point on the boundary that yields the maximum overall effectiveness to cost ratio would be the preferred solution if one adopts the approach of maximising returns on cost.

A notational point to note is that the transition years shown in the results of the case studies are all abbreviated to the last two digits. That is, 97 and 05 mean 1997 and 2005 respectively. The current year is 1989.

A. CASE STUDY 1: STATIONARY ENVIRONMENT

The first scenario we examine is one in which the only change occurring is that due to deterioration. Technology and requirement levels are at a standstill and no inflation occurs. The value of money is constant over time, i.e., interest rate is zero. This highly improbable scenario is implied by the commonly used "equal life" assumption whereby an alternative, once selected, will be selected over and over again and will always have the same service life.

Supposing alternatives 1 and 2 have the following cost and effectiveness characteristics shown in Table 6.2 and 6.3. Alternative 2 is thus three times as expensive to acquire but has a longer range and offers lower maintenance and operating costs than Alternative 1. Requirement levels are assumed constant at 95 nm for range, 80% for accuracy and 70% for availability. Results of analysis performed using the prototype DSRPM for this case is presented in Table 6.4 below.

TABLE 6.2: Characteristics of Alternative 1

MOE	Value When New	ρ_1	Cost Parameters						
Range(nm)	120	-0.03	Acquisition	Maintenance		Operating		Salvage	
Accuracy (%)	95	-0.02	AC_1	k_1	γ_1	OC_1	δ_1	SV_1	σ_1
Availability (%)	95	-0.03	100	30	1.3	7	0.05	-50	-0.2

The value of the total life-cycle cost and effectiveness are plotted in Figure 6.1. As interest rate is zero, MAAC and MAC approaches yielded the same solution. The results show that an alternative that is selected will be selected repeatedly in the future, the service life each time being the same. This is only to be expected as, under static conditions, there are no reasons for change. Note that the solution that

TABLE 6.3: Characteristics of Alternative 2

MOE	Value When New	ρ_2	Cost Parameters						
Range (nm)	140	-0.03	Acquisition	Maintenance		Operating		Salvage	
Accuracy (%)	95	-0.02	AC_2	k_2	γ_2	OC_2	δ_2	SV_2	σ_2
Availability (%)	95	-0.03	300	15	13	4	0.05	-90	-0.2

TABLE 6.4: Results for Stationary Environment

Solution	Total LCC	Total LCE	LCE/LCC	Alt. Chosen			Transition Year			λ_i^*
Approach	(3 Systems)	(3 Systems)	Ratio	1	2	3	1	2	3	
MAAC	1206.05	16.550	0.01372	0	2	2	91	99	07	
MAC	1206.05	16.550	0.01372	0	2	2	91	99	07	
SECR	1097.35	15.062	0.01373	0	2	2	89	97	05	
LR	1270.84	17.265	0.01359	0	2	2	89	00	08	0
LR	1206.05	16.550	0.01372	0	2	2	91	99	07	0.01104
LR	1147.33	15.816	*0.01379	0	2	2	90	98	06	0.01251
LR	801.84	10.934	0.01364	0	1	1	90	95	00	0.01413
LR	751.86	10.179	0.01354	0	1	1	89	94	99	0.01509

gives the maximum return per unit cost for the three systems overall (marked with an asterisk in Table 6.4 and a square in Figure 6.1) is different from that obtained using the SECR approach. The overall LCE to OCC ration in the case of the SECR solution is not as high even though the solution also lies on the efficiency boundary. The implication of this is obvious - maximizing return per unit cost for individual systems considered separately leads to a good but not best solution in terms of overall return per unit cost.

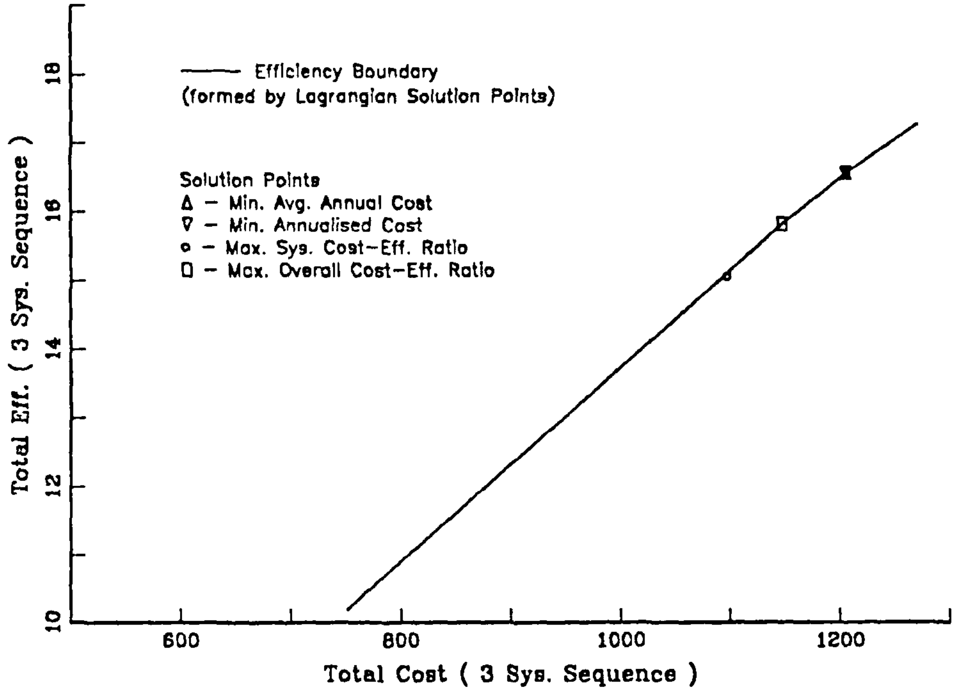


Figure 6.1: Stationary Environment Case Study Results

B. CASE STUDY 2: INFLATION AND INTEREST RATES

The next scenario we look at is probably the one most commonly encountered in a typical system renewal study. Future inflation and interest rates are assumed to be non-zero and constant, and future technological advancements and changes in requirement levels are ignored. For illustrative purposes, let us say the inflation and interest rates were projected to be constant at four and five percent per annum respectively. Cost projections based on these rates are shown in Figure 6.2 in the sample input file for this case study (Appendix B). Analysis based on this scenario produced the results shown in Table 6.5.

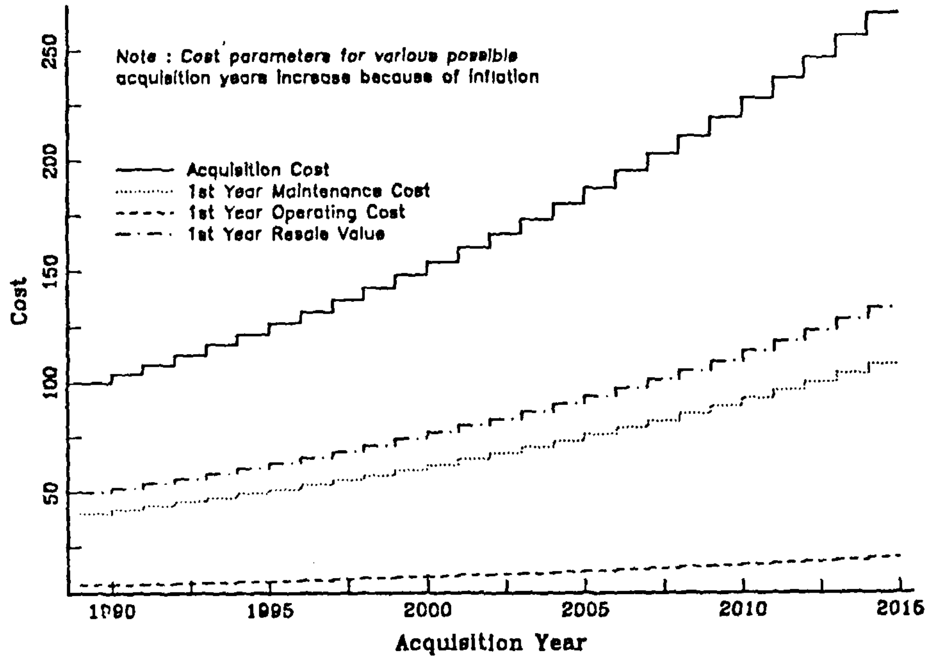


Figure 6.2 a : Cost Evolution for New Alternative 1

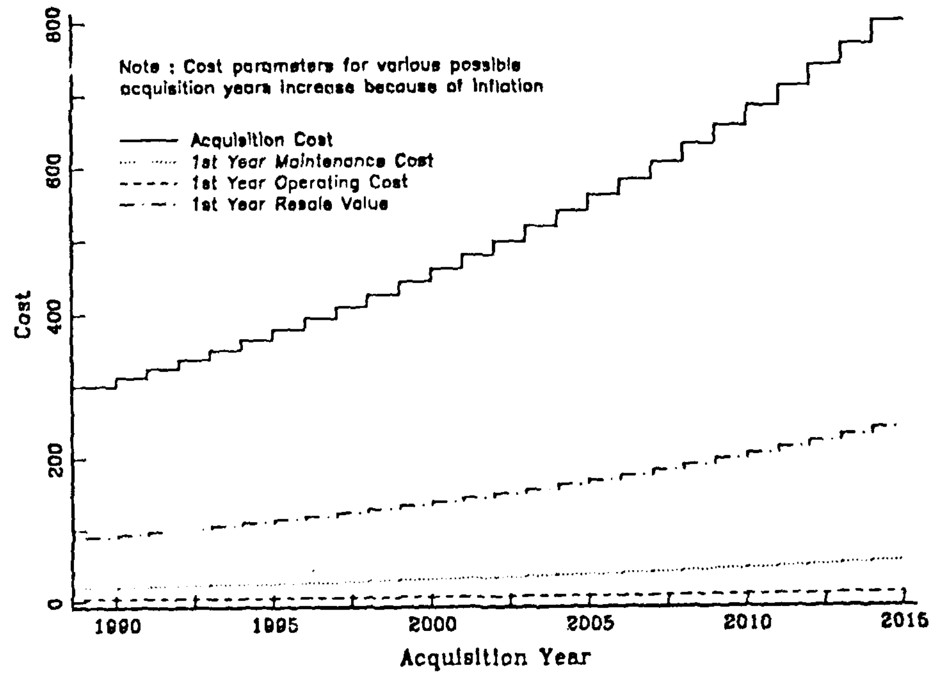


Figure 6 2 b : Cost Evolution for New Alternative 2

Figure 6.2 : Evolution of Cost Parameters for Alternatives 1 and 2 With Inflation (No Technological Progress)

TABLE 6.5: Results for Inflation and Interest Rates

Solution	Total LCC	Total LCE	LCE/LCC	Alt. Chosen			Transition Year			λ_i^*
Approach	3 Systems	3 Systems	Ratio	1	2	3	1	2	3	
MAAC	1031.26	17.266	0.01674	0	2	2	92	00	08	
MAC	811.98	13.375	0.01647	0	2	1	90	98	03	
SECR	921.03	14.396	0.01563	0	2	2	91	97	04	
LR	1031.26	17.265	0.01674	0	2	2	92	00	08	0
LR	986.44	16.550	⋆0.01678	0	2	2	91	99	07	0.01596
LR	944.29	15.816	0.01675	0	2	2	90	98	06	0.01742
LR	811.98	13.375	0.01647	0	2	1	90	98	03	0.01845
LR	683.34	10.934	0.01600	0	1	1	90	95	00	0.01898
LR	643.73	10.179	0.01581	0	1	1	89	94	99	0.01904

Total LCC and LCE from this table are plotted in Figure 6.3. The efficiency boundary is shifted towards lower cost since the interest rate is higher than the inflation rate. An opposite movement would occur if the converse was true. Note that the shift is greater for the higher cost end because inflation and interest rates have a bigger impact there. As the interest rate is significantly non-zero, we see that the solutions obtained using the $MAAC$ and MAC approaches are different. Note also that the SECR solution is clearly inferior as it lies somewhat below the efficiency boundary. From the above table, we can see that Alternative 1 is the low-end alternative. The last line in the table shows the solution that meets the specified minimum requirements at the lowest possible total cost, which is the one where the service lives of all three systems are at their minimums.

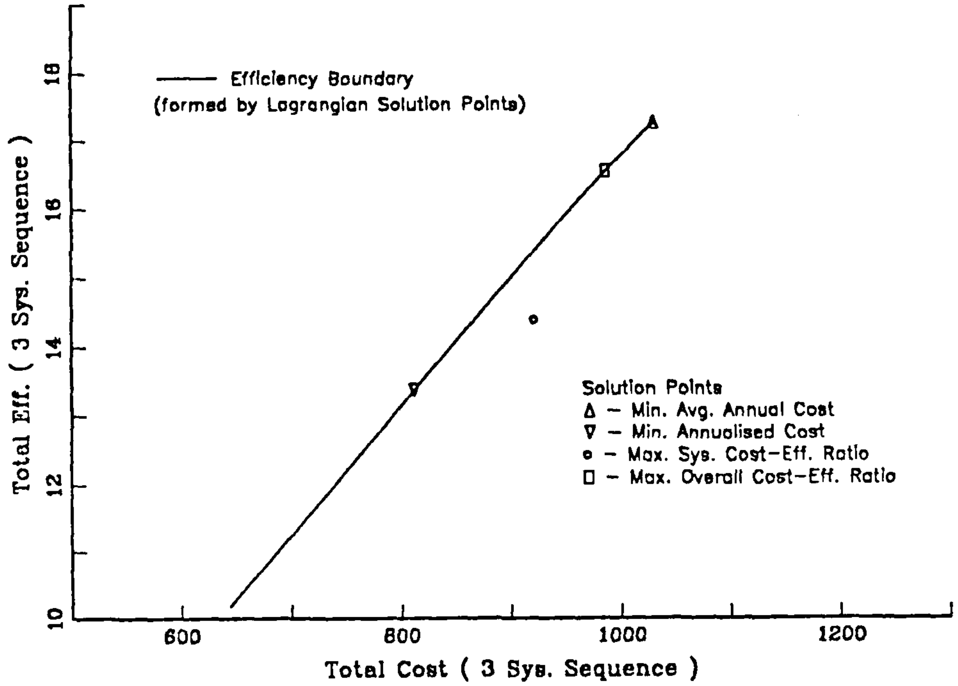


Figure 6.3: Inflation and Interest Rate Case Study Results

C. CASE STUDY 3: TECHNOLOGICAL ADVANCEMENT

For this scenario, let us suppose that technological progress has the effect of suppressing cost growth due to inflation from four to two percent per annum. The revised cost projections are shown in Figure 6.4. The sample input file for this case study is shown in Appendix B. In addition, technological advances are also reflected in improvement in performance characteristics. For the purpose of this case study, let us suppose that the various MOEs evolve as shown in Figure 6.5 and the sample input file in Appendix B. Improvements are primarily in range, with Alternative 1 becoming marginally better than Alternative 2 about ten years from now. Other conditions are as assumed in Case Study 2. The results for this case study are shown in Figure 6.6 and Table 6.6.

Contrasting Table 6.5 and Table 6.6, we note that Alternative 1 is now the dominantly favored alternative because it became competitive performance-wise as well as cost-wise. Technological advancement resulted not only in a further shift in the efficiency boundary towards lower cost but also an extension into higher levels of cumulative effectiveness. The lower end of the boundary is not affected as much as solutions in the higher end that extends further into the future. Note that technological advancement also results in lengthening of the maximum service life (three systems), as evident in the maximum effectiveness solution identified by $\lambda^* = 0$. In Case Studies 1 and 2, no solutions extend beyond the year 2008 whereas in this case study, some solutions extend to the year 2009.

TABLE 6.6: Results for Technological Advancement

Solution Approach	Total LCC 3 Systems	Total LCE 3 Systems	LCE/LCC Ratio	Alt. Chosen 1	2	3	Transition Year 1	2	3	λ_i^*
MAAC	888.11	18.491	0.02082	0	1	1	92	00	09	
MAC	736.01	14.509	0.01971	0	1	1	91	99	04	
SECR	804.94	16.220	0.02015	0	1	1	92	99	06	
LR	907.83	18.775	0.02068	0	2	2	92	00	09	0
LR	888.11	18.491	⋆0.02082	0	1	1	92	00	09	0.01444
LR	634.53	12.219	0.01926	0	1	1	91	96	01	0.02473
LR	601.75	11.366	0.01889	0	1	1	90	95	00	0.02601
LR	574.70	10.506	0.01828	0	1	1	89	94	99	0.0318[illegible]

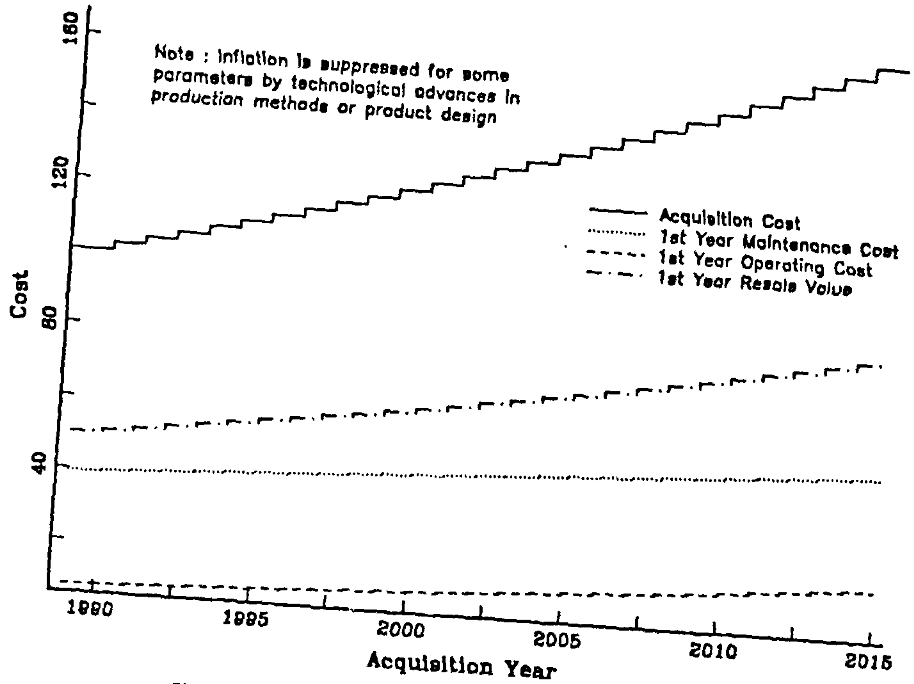


Figure 6.4 a : Cost Evolution for New Alternative 1

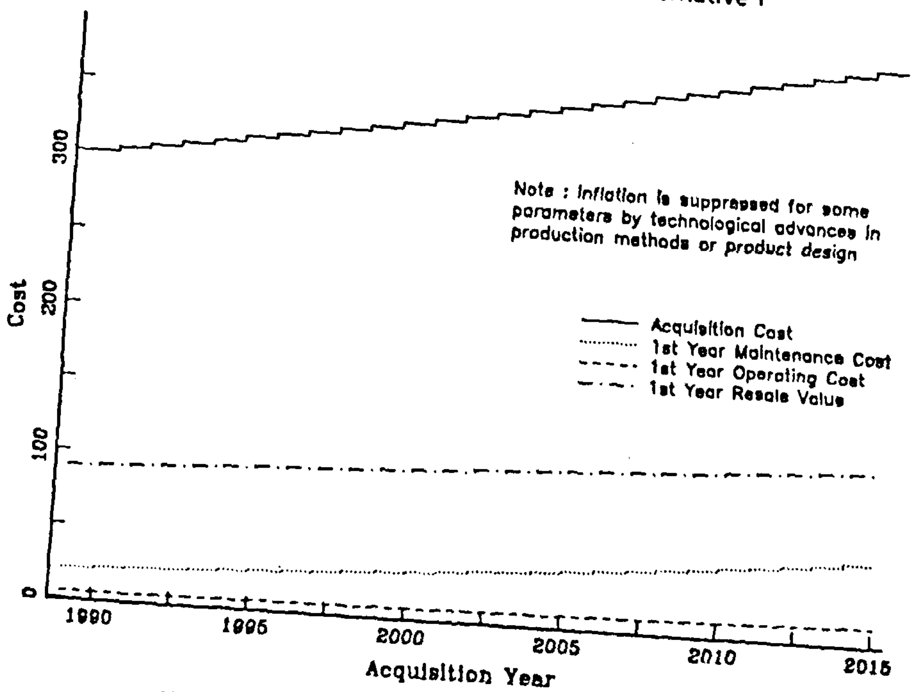


Figure 6 4 b : Cost Evolution for New Alternative 2

Figure 6.4 : Evolution of Cost Parameters for Alternatives 1 and 2 With Inflation and Technological Progress

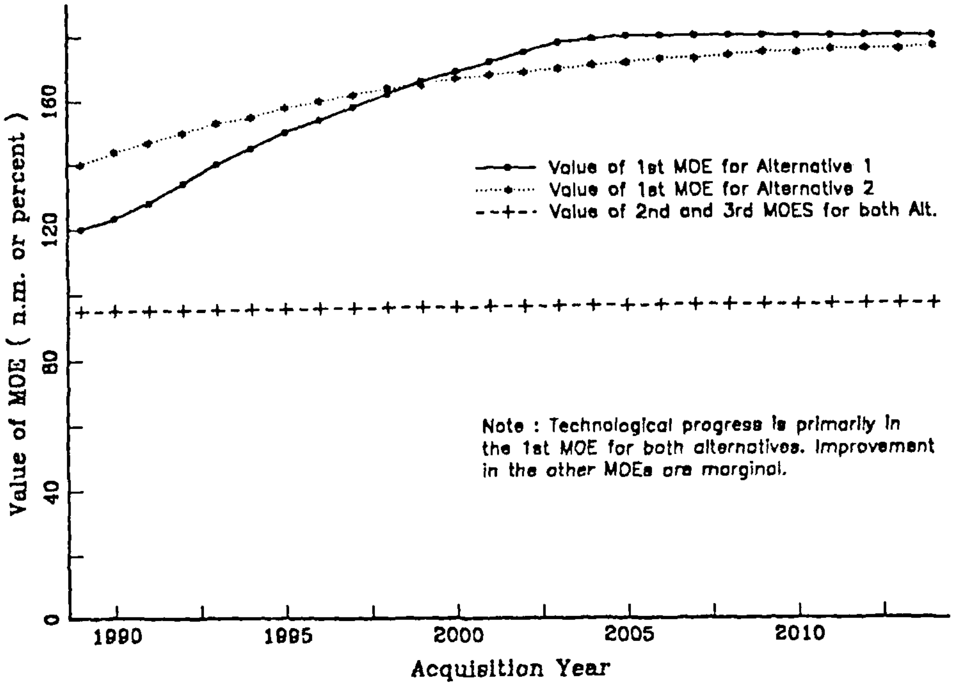


Figure 6.5: Evolution of MOEs With Technological Progress

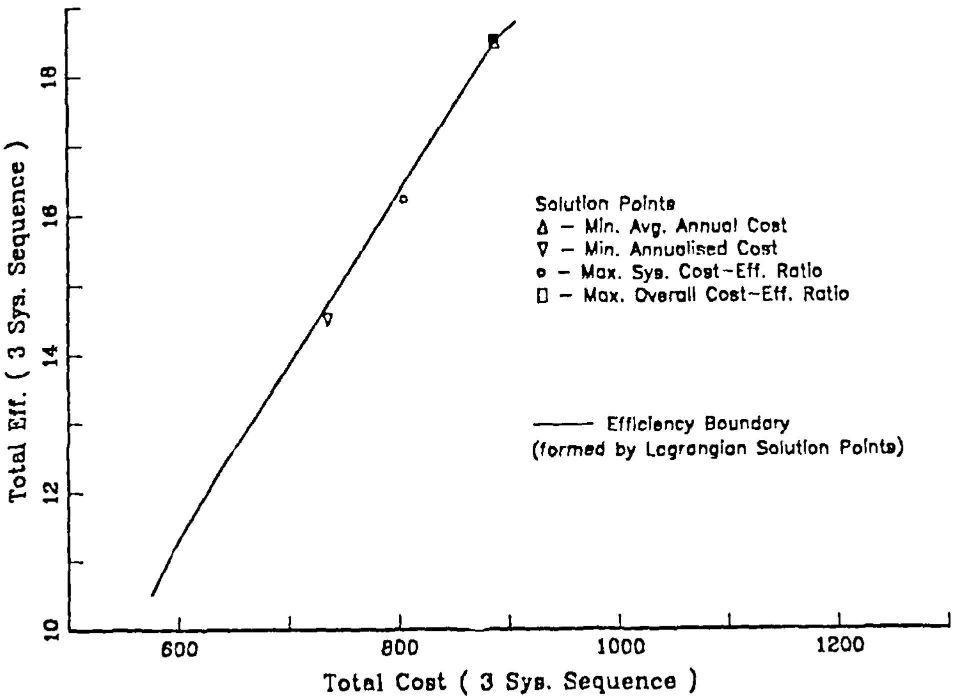


Figure 6.6: Technological Advancement Case Study Results

D. CASE STUDY 4: REQUIREMENT ESCALATION

Let us suppose that everything is as before, except that requirement levels set for range and availability increase over time as shown in Figure 6.7. The results for this scenario are shown in Table 6.7 and illustrated in Figure 6.8.

TABLE 6.7: Results for Requirement Escalation

Solution	Total LCC	Total LCE	LCE/LCC	Alt. Chosen			Transition Year			λ_i^*
Approach	3 Systems	3 Systems	Ratio	1	2	3	1	2	3	
MAAC	741.62	14.498	0.01955	0	1	1	91	96	04	
MAC	741.62	14.498	0.01955	0	1	1	91	96	04	
SECR	771.83	14.865	0.01926	0	2	1	91	98	04	
LR	872.43	16.431	0.01883	0	2	2	91	98	06	0
LR	835.93	16.395	⋆0.01961	0	2	1	91	98	06	0.00097
LR	741.62	14.498	0.01955	0	1	1	91	96	04	0.02011
LR	634.53	12.219	0.01926	0	1	1	91	96	01	0.02129
LR	574.70	10.506	0.01828	0	1	1	89	94	99	0.02863

Comparing Figures 6.6 and 6.8, we can see that the escalation in requirement levels resulted in a downward depression of the higher cost end of the efficiency boundary. This happens because the escalation in requirement levels results in the shortening of service lives only if the solution path extends far enough to be affected. Note that the maximum effectiveness solution, for instance, now extends only until the year 2006 whereas in the previous case study it reaches the year 2009. An interesting result in the equality of the $MAAC$ and MAC solutions even though the interest rate is five percent per annum. Note also that solutions calling for the first transition to be made in 1991 are clearly dominating.

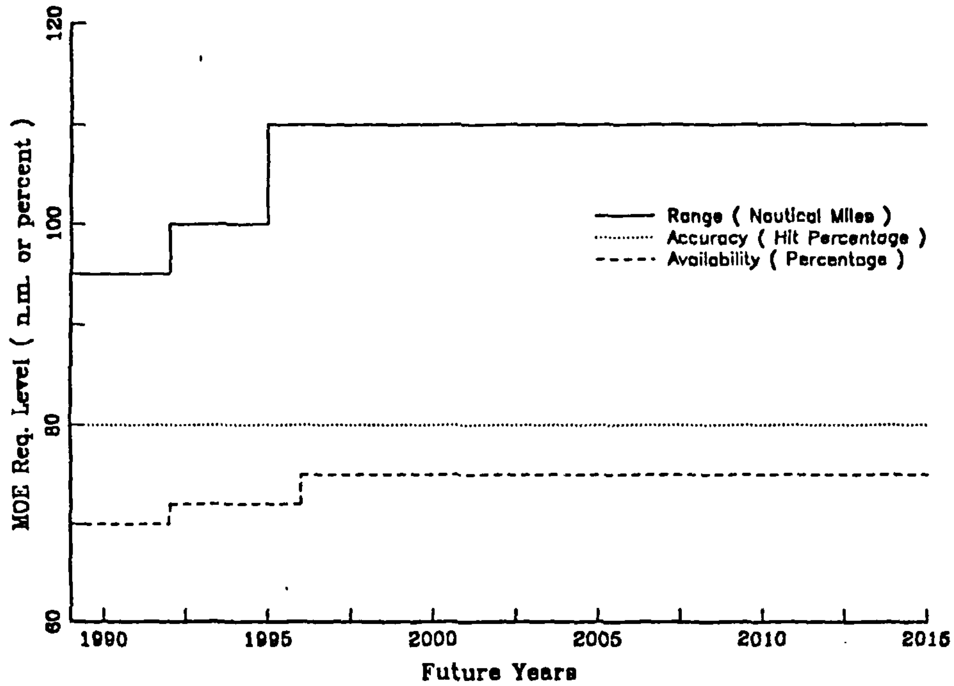


Figure 6.7: Escalation in Requirement Levels

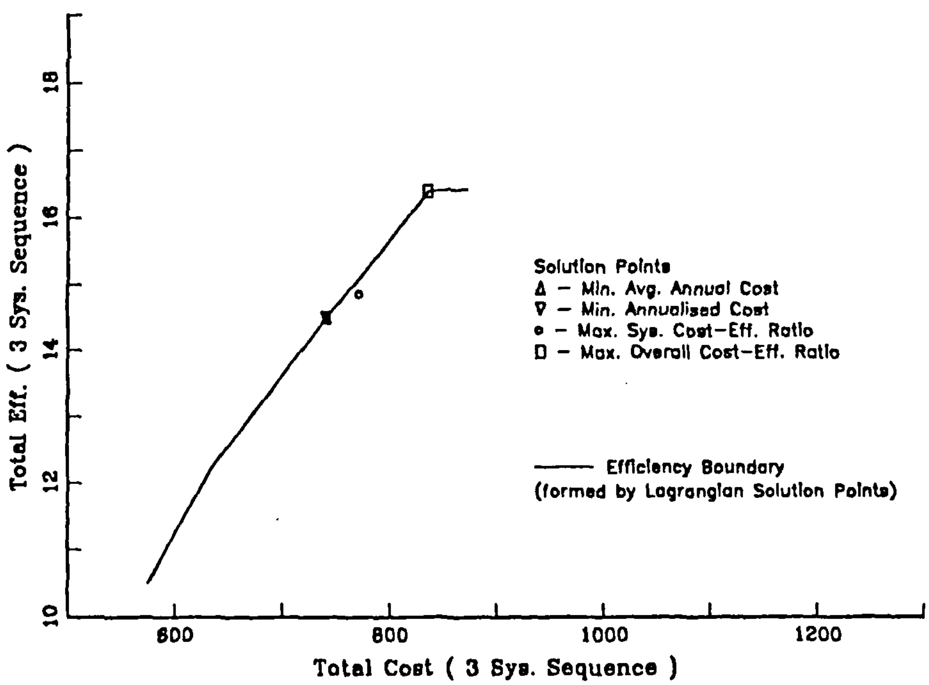


Figure 6.8: Requirement Escalation Case Study Results

E. CASE STUDY 5: SCHEDULING OF UPGRADES

Supposing Alternative 1 is an upgrading option, the exercise of which is significantly cheaper if carried out along with major scheduled overhauls. If such maintenance is carried out every three years, (e.g., refit of a ship), and the savings is say twenty percent, then the acquisition cost of a new Alternative 1 varies as illustrated in Figure 6.9. In this scenario, everything else is as assumed for Case Study 4.

The results for this scenario are given in Table 6.8 and Figure 6.10. As evident from the table, there are no saving realised in the higher cost end where the discounts are not taken up. The lower end of the efficiency boundary shifts to the left as a result of the savings. We see that the solution offering maximum effectiveness per unit cost suggests that the incumbent should be replaced with Alternative 2 in 1990, then upgraded with Alternative 1 in 1997 (a non-maintenance year with no discount) for use until the year 2005. The SECR solution also indicates an upgrade carried out in a non-maintenace year (1998). The overall desirability of matching a major upgrading program to some maintenance schedule to minimise downtime or to secure some savings can thus be evaluated using the model.

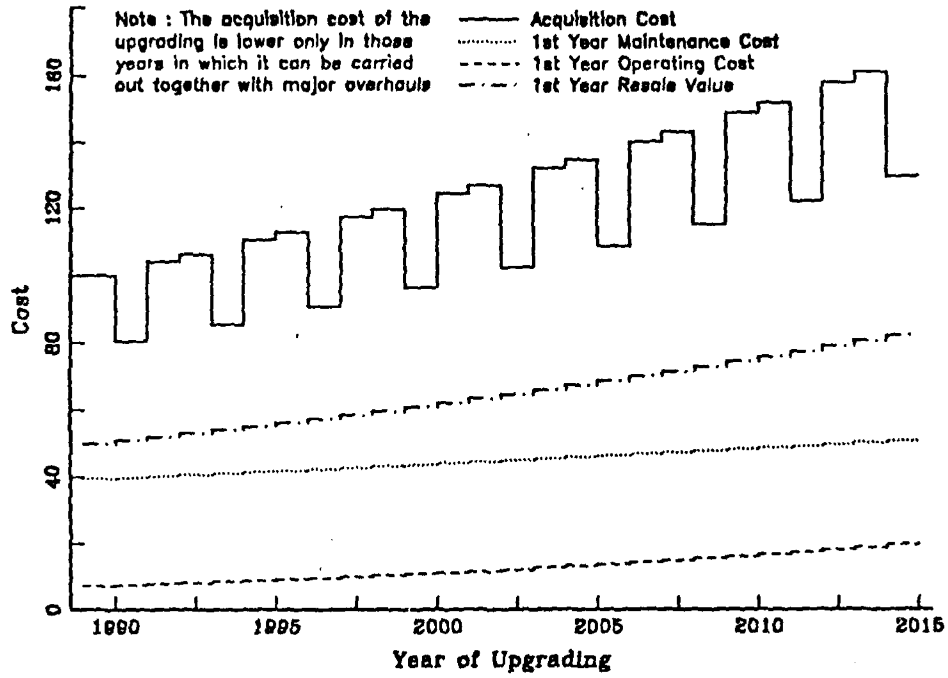


Figure 6.9: Evolution of Cost Parameters With Scheduled Overhauls

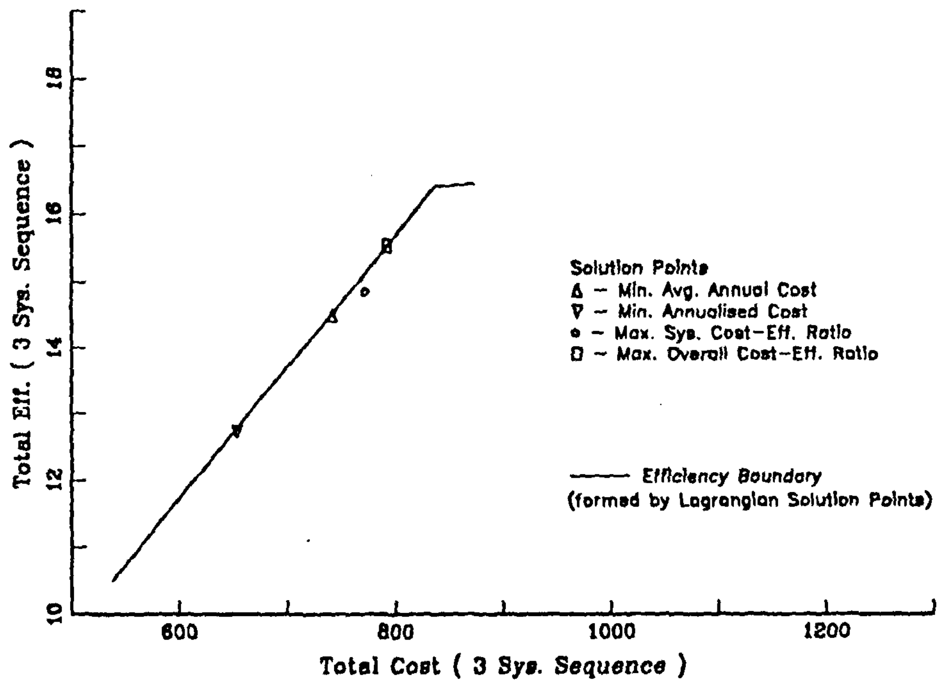


Figure 6.10: Scheduling of Upgrading Case Study Results

TABLE 6.8: Results for Upgrade Scheduling

Solution	Total LCC	Total LCE	LCE/LCC	Alt. Chosen			Transition Year			λ_i^*
Approach	3 Systems	3 Systems	Ratio	1	2	3	1	2	3	
MAAC	741.62	14.498	0.01955	0	1	1	91	96	04	
MAC	653.39	12.734	0.01949	0	1	1	89	94	02	
SECR	771.83	14.865	0.01926	0	2	1	91	98	04	
LR	872.43	16.431	0.01883	0	2	2	91	98	06	0
LR	835.93	16.395	0.01961	0	2	1	91	98	06	0.00097
LR	791.73	15.532	$\star$0.01962	0	2	1	90	97	05	0.01953
LR	538.06	10.506	0.01953	0	1	1	89	94	99	0.01981

Note: In this case study, a 1 for alternative chosen represents an upgrade of the preceding system. Thus the sequence 0,2,1 means the incumbent is replaced with alternative 2 and then upgraded with alternative 1.

F. CASE STUDY 6: DEVELOPMENT LEAD TIME

Let us suppose that everything is as in Case Study 5 except that Alternative 1 is an upgrade that requires one year of development and cannot be introduced immediately. The impact of such lead-time requirements can be seen in Table 6.9 and Figure 6.11. From the table, we can see that the lowest cost solution (bottom of table) still involves an immediate transition as in the other case studies. However, the transition is to Alternative 2 in this case as the model now bars the immediate execution of Alternative 1. The diagram clearly shows that the lead-time requirement pushes up cost at the lower cost end of the efficiency boundary. The MAAC solution, the SECR solution and the maximum effectiveness per unit cost solution are all unaffected. The MAC solution, however, became equal to the MAAC solution (curiously). Note that the MAC solution in Case Study 5 involved immediate

introduction of Alternative 1 (upgrade of alternative 0 preceding it); a solution that is not admissible in this case study.

TABLE 6.9: Results for Development Lead-Time

Solution	Total LCC	Total LCE	LCE/LCC	Alt. Chosen			Transition Year			λ_i^*
Approach	3 Systems	3 Systems	Ratio	1	2	3	1	2	3	
MAAC	741.62	14.498	0.01955	0	1	1	91	96	04	
MAC	741.62	14.498	0.01955	0	1	1	91	96	04	
SECR	771.83	14.865	0.1926	0	2	1	91	98	02	
LR	872.43	16.431	0.01883	0	2	2	91	98	06	0
LR	835.93	16.395	0.01961	0	2	1	91	98	06	0.00097
LR	791.73	15.532	⋆0.01962	0	2	1	90	97	05	0.01953
LR	741.62	14.498	0.01907	0	1	1	91	96	04	0.02063
LR	634.53	12.219	0.01926	0	1	1	91	96	01	0.02129
LR	621.31	10.754	0.01731	0	2	1	89	94	99	0.11078

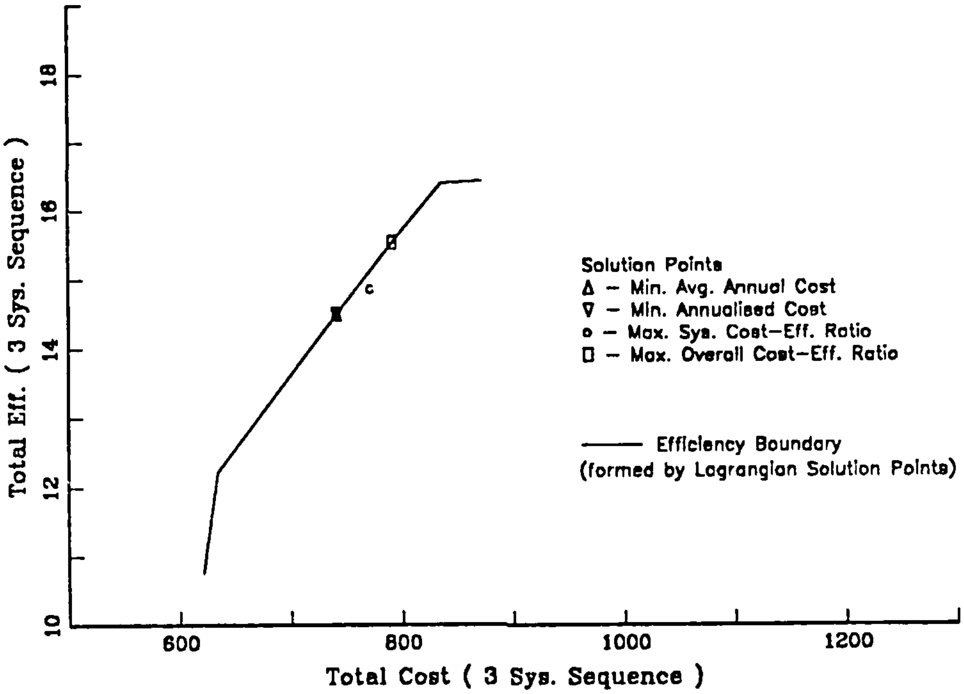


Figure 6.11: Development Lead Time Case Study Results

G. GENERAL OBSERVATIONS

From the series of six case studies analysed using the prototype DSRPM, we saw the impact of various issues as they were integrated into the model. DSRPM offers a common framework for decision makers to explore the consequences of various possibilities. It does not advocate any single solution for a given scenario, but rather maps out the efficiency boundary spanning the entire solution space and indicates the solutions obtained using various approaches. A plot of the results for various scenarios, as is done in Figure 6.12 for the case studies, gives the decision maker a good overview of the problem. The picture can be enriched by varying the shade of the result for each scenario according to its likelihood of occurrence. Furthermore, a third axis indicating overall service time for the three systems can be added as

in Figure 6.13 to give fuller expression to the problem. As explained in Chapter 2, the system renewal problem is basically a three-dimensional one - cost, effectiveness and time.

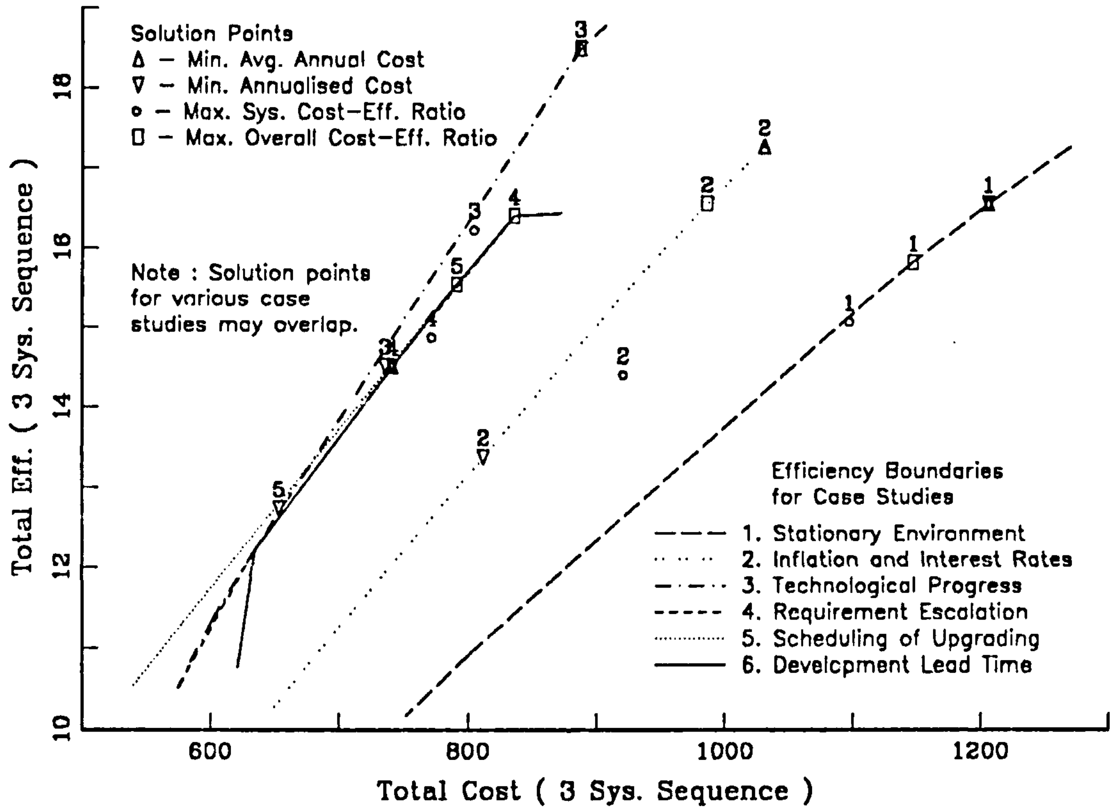


Figure 6.12: Consolidated Results for Case Studies

Although three systems are analysed in the model, the focus is really on when the first transition should take place and what alternative should be selected to succeed the incumbent system. Analysis may reveal a dominating (good under all scenarios) or robust (favored under most scenarios) solution to the timing and choice involved in the first transition. For example, the escalation of requirement in Case Study 4 resulted in hastening of the first transition by a year for the maximum

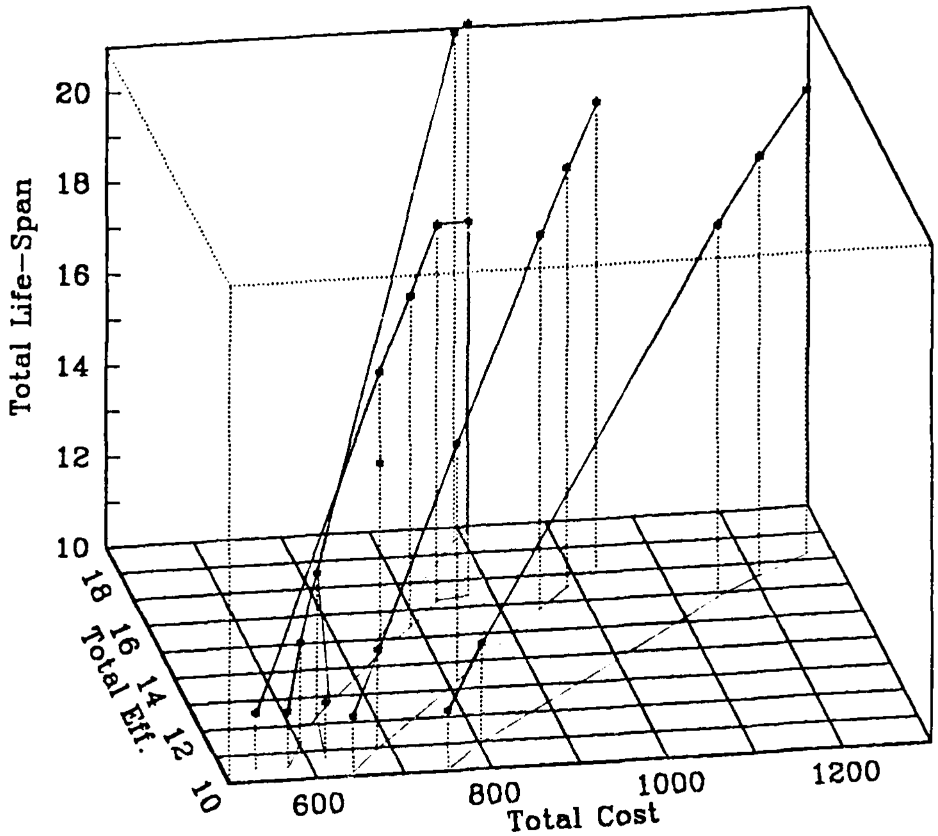


Figure 6.13: 3-D Plot of Efficiency Boundaries

overall effectiveness to cost ratio solution. In Case Study 6, however, we saw that this solution was not affected by the development lead time of one year. By varying the scenarios for various requirement escalation trends, development lead time estimates, etc., we can test the sensitivity of various solutions to variations in estimates and trends. Even if analysis proved inconclusive, a rough idea of how long the incumbent is likely to be kept will emerge. No commitment needs to be made if the time to the likely date of the first transition is more than the lead time required to effect the likely transition. For example, if analysis shows that an EW suite upgrade of a frigate should take place three years down the road and such an upgrade has a lead

time of two years, we needn't make a commitment yet, but we know the decision is due a year from now. At that time, the model can be run again with updated information. In this way, we can ensure decisions are made in a timely, fashion using the latest information.

Besides facilitating timely, consistent and rational decision-making, the model also looks forward to the future to provide estimates of cost, effectiveness and service life that facilitates good planning. If aggregated to sufficiently high levels, the model allows future year procurement budgets to be forecasted. Designs and support plans for succeeding systems can be optimised to service lives that are more realistic in terms of broad economic, technological and operational outlook. Amortization periods would no longer need to be arbitrarily assumed and budgets can be better planned knowing cost estimates of succeeding systems. The anticipated system selections also serves to better guide planning for defense infrastructure, R&D and other strategic concerns. The explicitness of the model fosters better consensus building and coordination among the various agencies responsible for system renewal planning. As discussed in Chapter 4, Section E, force level and mix issues as well as phased build-up versus bulk procurement decisions can also be dealt with by the DSRPM. The model thus provides a comprehensive and systematic framework for system renewal decisions to be made optimally and in a consistent and timely manner based on current forecasts.

Lastly, it should be noted that inflation and interest rates were assumed constant and linear utility functions were used in the case studies for reason of convenience and not necessity. The model allows these rates and effectiveness requirement levels to be varied for future years in a scenario. Long-range projections can be varied more than near-term ones to account for greater uncertainty in these projections. The impact of technological advancement is also freely interpreted in terms

of changes in cost and effectiveness parameter projections and no restrictions are placed on the definition of utility functions. The DSRPM thus affords very flexible means to model the factors influencing systems renewal problems.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The dynamic system renewal planning model (DSRPM) provides a systematic framework within which optimal system renewal decisions may be made in a consistent and timely manner, under realistic conditions of changing environments. Conceptually, it embodies a concept of obsolescence that is more comprehensive, better formalised and more relevant to military planners than is available in current literature. Prediction of what future renewals are likely to be made and when, and estimation of the associated cost and effectiveness would allow plans to be made anticipatively with a long-term perspective. Through simple reformulation and use of shadow prices, bulk versus phased procurement decisions as well as force level and mix issues can also be examined using the model.

The plausibility and usefulness of the model was demonstrated by a series of case studies using the prototype that was developed. The equal life assumption often used in system renewal models was illustrated by the first case study. Other case studies showed the impact of interest and inflation rates, technological progress, requirement escalation and development lead time. Application of the model to the scheduling of upgrades that are cheaper to carry out during overhaul periods was also shown.

The prototype DSRPM illustrates how the model may be used as a descriptive decision aid to better understand the complex effects of a diverse range of issues on the system renewal decision. It was shown how the model organises financial, operational, intelligence and other staff projections within an integrated framework to

provide decision makers with a broad, consistent, long-term perspective of relevant issues. The decision maker is presented with a graphic picture of the entire solution space as structured by the system renewal scenarios considered. Scenarios are flexibly modelled and are used to point to solutions that are robust in the face of uncertainty. By continually refining scenarios based on lessons learned from exercises, audits, and other new information on trends, past experience is brought to bear on the present so that the basis of decisions is kept current and realistic. The communication among all parties involved in this process is facilitated by the explicitness of the model. This in turn fosters consensus building necessary for cohesive effort in defense planning.

The model that was developed is a conceptual prototype that is as yet untested by a real application. Much remains to be done before it is ready for organisation-wide implementation. However, it holds much promise and should be examined further for future implementation.

B. RECOMMENDATIONS

The prototype that was developed is a rudimentary one that could be extended in many ways as future research topics. It is recommended that research proceed in the following order of tractability:

1. Factoring foreign exchange rates into the model is a desirable goal. The treatment of interest and inflation rates would, however, require some adjustments.

2. Optimal force mix can be determined if shadow prices of different components of a task force are made compatible. Means of integrating the utility functions of these components under a common mission structure needs to be examined.

3. Simulation and forecasting capabilities can be incorporated to better explore the range of system renewal scenarios that may be encountered in the future.

4. Stochastic models can be constructed to better portray uncertainty in cost, effectiveness and requirement levels.

5. Utility modelling may be facilitated by the use of implicit approaches that do not require utility functions to be explicitly defined over the entire domain of the MOE value.

6. System renewal models developed for various systems could be linked and aggregated to higher entities using schemes that incorporate organisation structure into the solution algorithm to avoid sub-optimisation. Plans developed for ships could, for example, be tied to plans for their operational task forces and administrative units. The ideal would be to achieve a level of aggregation high enough to interface with arms race and econometric models so that very high levels of optimisation may be achieved.

7. Fuzzy set and logic theory may be introduced to better model elements that are inherently vague. Requirement levels, for example, may be made elastic by using what is known as fuzzy numbers. This may allow some form of abstract qualitative reasoning to be represented in the model.

APPENDIX A: PROGRAM LISTINGS

```
preamble

   normally, mode is real, dimension is 0

   permanent entities

      every YEAR has a DISCOUNT.FACTOR and a CUM.DF

   normally, mode is integer

      every NODE has a TRANS.YEAR, a SYS.CODE,
                     a BEST.PRED.NODE and a BEST.PRED.ARC
      every ARC has a TAIL and an ALT.CODE
      every SYS has a MIN.LIFE, a MAX.LIFE, a NUM.NODES, a NUM.ARCS and
                    a BASE.YEAR
      every ALT has an ALT.NAME and a LEAD.TIME

   define MOE, MOE.DF as 3-dimensional real arrays
   define AC, MC.P1, MC.P2, OC, OC.EF, DC, DC.EF, SV, SV.EF and
          MIN.MOE.REQ as 2-dimensional real arrays
   define MOE.NAME as a 1-dimensional text array
   define L and CRIT.FUNC as 1-dimensional double arrays
   define LCE, LCC, MOE.WT, O.MOE and O.MOE.DF as 1-dimensional
          real arrays
   define MAX.PRED.NODES, LIM.MOE and EP as 1-dimensional integer arrays
   define ARGMAX.CF, ARG.MAC, ARG.AAC, CURR.YEAR, NUM.MOE and NUM.ALT as
          integer variables
   define LAMDA, LAMDA1, LAMDA2, LAMDA3, SUM.LCC, SUM.LCC.1, SUM.LCC.2,
          SUM.LCE, SUM.LCE.1, SUM.LCE.2, MAX.LCE, MIN.LCC, MOE.VALUE,
          SLOPE1, SLOPE2, SLOPE3, L1, L2, L3, BUDGET, AMC, AOC, DCY,
          SVY, O.MC.P1, O.MC.P2, O.OC, O.OC.EF, O.DC, O.DC.EF, O.SV,
          O.SV.EF, MAX.MAC, MAX.AAC, AAC.CF, INT.RATE and INT.DF as
          real variables
   define MAX.CF as a double variable  '' Double means double precision.
   define APPROACH, ECHO.ON, CASE.NAME and ALT.NAME as text variables

end
```

```
main

   call INITIALIZE

   if APPROACH = "Lagrangian"
      call LAGRANGIAN
   else
      call BEST.PATH
      call SUM.LCC.LCE
   always

   call RESULTS.PRINT

   stop

end
```

```
routine INITIALIZE

   open 1 for input, name is "IN.DAT"
   use 1 for input
   open 2 for output, name is "OUT.DAT"
   use 2 for output

   read CASE.NAME
   read N.SYS, N.ALT, NUM.MOE, CURR.YEAR, INT.RATE
   read ECHO.ON

   create every SYS and ALT

   N.YEAR = 1
   for I = 1 to N.SYS
   do
      read MIN.LIFE(I) and MAX.LIFE(I)  '' Computing number of years to
      N.YEAR = N.YEAR + MAX.LIFE(I)     '' be covered in the analysis.
   loop

   create every YEAR

   for I = 1 to N.ALT
      read ALT.NAME(I) and LEAD.TIME(I)
   read DISCOUNT.FACTOR(1)
   CUM.DF(1) = DISCOUNT.FACTOR(1)
   for I = 2 to N.YEAR
   do
      read DISCOUNT.FACTOR(I)
      CUM.DF(I) = CUM.DF(I-1) * DISCOUNT.FACTOR(I)
   loop
   read APPROACH      '' Determines the type of solution to be generated
   read BUDGET        '' Used only in the Lagrangian approach

   '' Allocating memory to arrays
   reserve MAX.PRED.NODES(*) as N.SYS
   reserve AC(*,*), MC.P1(*,*), MC.P2(*,*), OC(*,*), OC.EF(*,*),
           DC(*,*), DC.EF(*,*), SV(*,*), SV.EF(*,*) as N.ALT by N.YEAR
   reserve MOE(*,*,*) and MOE.DF(*,*,*) as N.ALT by NUM.MOE by N.YEAR
   reserve MOE.NAME(*), MOE.WT(*), O.MOE(*), O.MOE.DF(*) as NUM.MOE
   reserve MIN.MOE.REQ(*,*) as NUM.MOE by N.YEAR

   call CALC1.NODE      '' Structuring the network.

   create every NODE and ARC
   reserve CRIT.FUNC(*) as N.NODE
   reserve EP(*) as (N.NODE + 1)
   reserve LCE(*), LCC(*), LIM.MOE(*) and L(*) as N.ARC

   call CALC2.NODE      '' Computing the year & system of each node
                        '' & the start index of arcs entering it.

   call CALC.ALT.CODE   '' Assigning code of alternatives.

   read O.MC.P1, O.MC.P2, O.OC, O.OC.EF, O.DC, O.DC.EF, O.SV, O.SV.EF
```

```
   for I = 1 to N.ALT
      for J = 1 to N.YEAR
         read AC(I,J), MC.P1(I,J), MC.P2(I,J), OC(I,J), OC.EF(I,J),
              DC(I,J), DC.EF(I,J), SV(I,J) and SV.EF(I,J)
   for J = 1 to NUM.MOE
      read MOE.NAME(J), MOE.WT(J), O.MOE(J) and O.MOE.DF(J)
   for J = 1 to NUM.MOE
      for K = 1 to N.YEAR
         read MIN.MOE.REQ(J,K)
   for I = 1 to N.ALT
      for J = 1 to NUM.MOE
         for K = 1 to N.YEAR
            read MOE(I,J,K) and MOE.DF(I,J,K)

   call CALC.ARC       '' Computes tail node, LCC and LCE for each arc.

   print 3 line with CASE.NAME thus
Dynamic End-Of-Life-Cycle Planning Model

Case of **************************************

   skip 1 line
   print 4 line with APPROACH and BUDGET thus
Approach - ******************     Budget = $*********.**

Note : Budget is used only for the Lagrangian relaxation approach and is
ignored in the other approaches.

   if ( ECHO.ON = "On" )
      call ECHO.INPUT

      skip 1 line
      print 9 line thus
Candidate Arcs For Solution Path

Note - LCC is made to be unfavorably high if the minimum requirement
level for any component MOE of LCE has not been met. The limiting MOE
is given as the highest index of the MOE(s) that failed to meet the
minimum requirement level(s) during the life-span covered by the arc.

Arc  Alt.  Tail  Head         Life-Cycle        Limiting
No.  Code  Node  Node   Effectiveness   Cost      MOE

   skip 1 line
   for I = 2 to N.NODE
      for K = EP(I) to ( EP(I+1) - 1 )
         print 1 line with K, ALT.CODE(K), TAIL(K), I, LCE(K), LCC(K)
            and LIM.MOE(K) thus
***  ***   ***   ***    ******.****  *****.**     ***
   always

   return

end
```

```
routine CALC1.NODE

   '' Structuring the network by determining the number of
   '' nodes and arcs in each system

   BASE.YEAR(1) = CURR.YEAR + MIN.LIFE(1)
   MAX.PRED.NODES(1) = 1
   NUM.NODES(1) = MAX.LIFE(1) - MIN.LIFE(1) + 1
   NUM.ARCS(1) = NUM.NODES(1)
   N.NODE = NUM.NODES(1) + 1
   N.ARC = NUM.ARCS(1)
   for I = 2 to N.SYS
   do
      J = I - 1
      BASE.YEAR(I) = BASE.YEAR(J) + MIN.LIFE(I)
      MAX.PRED.NODES(I) = NUM.NODES(I-1)
      NUM.NODES(I) = NUM.NODES(J) + MAX.LIFE(I) - MIN.LIFE(I)
      NUM.ARCS(I) = N.ALT * NUM.NODES(J) *
                     ( MAX.LIFE(I) - MIN.LIFE(I) + 1 )
      N.NODE = N.NODE + NUM.NODES(I)
      N.ARC = N.ARC + NUM.ARCS(I)
   loop

   return

end
```

```
routine CALC2.NODE

    '' Computes for each node information such as the year and system
    '' it belongs to, as well as the lead index ( contained in entry
    '' point array EP ) of the arcs entering the node

    TRANS.YEAR(1) = CURR.YEAR
    SYS.CODE(1) = 0
    EP(1) = 0
    K = 2
    JJ = 1
    for J = 1 to NUM.NODES(1)
    do
       TRANS.YEAR(K) = BASE.YEAR(1) + J - 1
       SYS.CODE(K) = 1
       EP(K) = EP(K-1) + 1
       K = K + 1
    loop
    for I = 2 to N.SYS
    do
       for J = 1 to NUM.NODES(I)
       do
          TRANS.YEAR(K) = BASE.YEAR(I) + J - 1
          SYS.CODE(K) = I
          EP(K) = EP(K-1) + JJ
          M = MAX.LIFE(I) - MIN.LIFE(I) + 1
          JJ = N.ALT*min.f(J,MAX.PRED.NODES(I),M,(NUM.NODES(I)-J+1))
          K = K + 1
       loop
    loop
    EP(N.NODE+1) = EP(N.NODE) + N.ALT

    return

end
```

```
routine CALC.ALT.CODE

   '' Assigns alternative codes to each arc.

   for K = 1 to NUM.NODES(1)
      ALT.CODE(K) = 0
   for I = ( NUM.NODES(1) + 2 ) to N.NODE
      for K = EP(I) to ( EP(I+1) - 1 )

         ALT.CODE(K) = ( mcd.f ( K - EP(I) , N.ALT ) + 1 )

   return

end
```

```
routine CALC.ARC

   '' Determines the tail node, life-cycle cost & effectiveness
   '' associated with each arc.

   '' Initialising LCE & Limiting MOE arrays
   for K = 1 to N.ARC
   do
      LCE(K) = 0
      LIM.MOE(K) = 0
   loop

   '' Computations for the present system ( system 1 ).
   '' All arcs here have the alternative code 0.
   for K = 1 to NUM.NODES(1)
   do
      TAIL(K) = 1
      M = TRANS.YEAR(K+1) - CURR.YEAR
      LCC(K) = O.DC * exp.f( O.DC.EF * M ) - O.SV * exp.f( O.SV.EF * M )
      for I = 1 to NUM.MOE
      do
         MOE.VALUE = O.MOE(I)                        '' LCC is made very high
         if ( MOE.VALUE < MIN.MOE.REQ(I,M+1) )       '' if any MOE require-
            LCC(K) = 9999999                         '' ment level is not met
            LIM.MOE(K) = I
         always
         '' Note : Utility fn. is Value / Max.Value
         if ( I = 1 )
            LCE(K) = LCE(K) + MOE.WT(I) * MOE.VALUE / 180
         else
            LCE(K) = LCE(K) + MOE.WT(I) * MOE.VALUE / 100
         always
      loop

      for J = 1 to M
      do
         AMC = O.MC.P1 * O.MC.P2 * ( J ** ( O.MC.P2 - 1 ) )
         AOC = O.OC * exp.f( O.OC.EF * J )
         LCC(K) = LCC(K) + ( AMC + AOC ) * CUM.DF(J)
         for I = 1 to NUM.MOE
         do
            MOE.VALUE = O.MOE(I) * exp.f( O.MOE.DF(I) * J )
            if ( MOE.VALUE < MIN.MOE.REQ(I,J+1) )      '' Checking if MOE
               LCC(K) = 9999999                        '' req. were met.
               LIM.MOE(K) = I
            always
            '' Note : Utility fn. is Value / Max.Value
            if ( I = 1 )
               LCE(K) = LCE(K) + MOE.WT(I) * MOE.VALUE / 180
            else
               LCE(K) = LCE(K) + MOE.WT(I) * MOE.VALUE / 100
            always
         loop
      loop
   loop
```

```
'' Computations for later systems, represented by
'' arcs with alternative code higher than 0.
for S = 2 to N.SYS
   for J = 3 to N.NODE
   with SYS.CODE(J) = S
      for I = 2 to N.NODE
      with SYS.CODE(I) = S - 1
      do
         M = TRANS.YEAR(J) - TRANS.YEAR(I)    '' Number of years used.
         if ( ( M >= MIN.LIFE(S) ) and ( M <= MAX.LIFE(S) ) )
            for N = 1 to N.ALT
            do
               TAIL(K) = I                    '' Start node of the arc K.
               DCY = DC(N,I) *
                     exp.f( DC.EF(N,I) * M )  '' Disposal cost &
               SVY = SV(N,I) *                '' salvage value in the
                     exp.f( SV.EF(N,I) * M )  '' last year.

               YR = TRANS.YEAR(I) - CURR.YEAR    '' No. of years
                                                 '' from the present.
               LCC(K) = AC(N,I) * CUM.DF(YR+1) +
                       ( DCY-SVY ) * CUM.DF(YR+1)
               for E = 1 to NUM.MOE
               do
                  MOE.VALUE = MOE(N,E,YR+1)
                  '' Note : Utility fn. is Value / Max.Value
                  if ( E = 1 )
                     LCE(K) = LCE(K) + MOE.WT(E) * MOE.VALUE / 180
                  else
                     LCE(K) = LCE(K) + MOE.WT(E) * MOE.VALUE / 100
                  always
                  if ( MOE.VALUE < MIN.MOE.REQ(E,YR+1) )
                     LCC(K) = 9999999            '' Checking if MOE
                     LIM.MOE(K) = E              '' req. were met.
                  always
               loop
               for Y = 1 to M
               do
                  AMC = MC.P1(N,I) * MC.P2(N,I) *     '' Annual maint.
                       ( Y ** ( MC.P2(N,I) - 1 ) )    '' & operating
                  AOC = OC(N,I) * exp.f( OC.EF(N,I) * Y )  '' costs.
                  LCC(K) = LCC(K) + ( AMC + AOC ) *
                          CUM.DF(YR+M)
                  for E = 1 to NUM.MOE
                  do
                     MOE.VALUE = MOE(N,E,YR+1) *
                                exp.f ( MOE.DF(N,E,YR+1) * Y )
                     '' Note : Utility fn. is Value / Max.Value
                     if ( E = 1 )
                        LCE(K) = LCE(K) + MOE.WT(E) * MOE.VALUE / 180
                     else
                        LCE(K) = LCE(K) + MOE.WT(E) * MOE.VALUE / 100
                     always
                     if ( MOE.VALUE < MIN.MOE.REQ(E,YR+Y+1) )
```

```
                                    LCC(K) = 9999999            '' Checking if MOE
                                    LIM.MOE(K) = E              '' req. were met.
                                 always
                              loop
                           loop
                           compute MAX.LCE as the      '' MAX.LCE & MIN.LCC are
                              maximum of LCE(K)        '' needed for computing
                           if ( LCC(K) < 9999999 )     '' the upper bound on the
                              compute MIN.LCC as the   '' Lagrangian multiplier.
                                 minimum of LCC(K)
                           always
                           K = K + 1
                        loop
                     always
                  loop

   return

end
```

```
routine ECHO.INPUT

   '' Echo of important inputs

   skip 1 line
   print 1 line thus
   Sys.Code  Min.Life  Max.Life  Base.Yr.  No.Nodes  No.Arcs
   For I = 1 to N.SYS
      print 1 line with I, MIN.LIFE(I), MAX.LIFE(I), BASE.YEAR(I),
         NUM.NODES(I), NUM.ARCS(I) thus
     ***       ***       ***       ****      ****      ****

   skip 1 line
   print 1 line thus
   Alternative Name        Alt.Code        Lead Time
   For I = 1 to N.ALT
      print 1 line with ALT.NAME(I), I, LEAD.TIME(I) thus
   ********************       ***             ***

   skip 1 line
   print 2 line thus
        Measure of Effectiveness                 Present System
Code      Name       Weightage                Level   Exp.RateOfChange
   for I = 1 to NUM.MOE
      print 1 line with I, MOE.NAME(I), MOE.WT(I), O.MOE(I), O.MOE.DF(I)
***  ***************   *.***               ******.***     ****.***

   return

end
```

```
routine LAGRANGIAN

   '' Solution by Lagrangian relaxation method

   '' The starting lower bound for the Lagrangian multiplier lamda is 0.
   '' The upper bound is determined such that it is barely sufficient to
   '' ensure that the corresponding slope will be positive. Variables
   '' may be overwhelmed,  even when double precision is used, if lamda
   '' or the cost values are too high.

   LAMDA1 = 0
   LAMDA2 = ( N.NODE * MAX.LCE / MIN.LCC ) + 1

   skip 1 line
   print 3 line thus
   Iterations of the Lagrangian Relaxation Method

Lamda1   Lamda3   Lamda2    Slope1  Slope3  Slope2    L1     L3     L2
   Skip 1 line

   '' Iterations by intercept of supporting planes method.

   'Iterate'

   LAMDA = LAMDA1
   call BEST.PATH
   call SUM.LCC.LCE
   SUM.LCC.1 = SUM.LCC
   SUM.LCE.1 = SUM.LCE
   SLOPE1 = -1 * ( SUM.LCC.1 - BUDGET )
   L1 = SUM.LCE.1 - LAMDA1 * ( SUM.LCC.1 - BUDGET )

   if ( SLOPE1 > 0 )
      skip 1 line
      print 2 line thus
   The budget is sufficient for cost to be no longer a constraint,
   ie. the solution is that of maximum effectiveness over time.
      return
   always

   LAMDA = LAMDA2
   call BEST.PATH
   call SUM.LCC.LCE
   SUM.LCC.2 = SUM.LCC
   SUM.LCE.2 = SUM.LCE
   SLOPE2 = -1 * ( SUM.LCC.2 - BUDGET )
   L2 = SUM.LCE.2 - LAMDA2 * ( SUM.LCC.2 - BUDGET )

   if ( SLOPE2 < 0 )
      skip 1 line
      print 4 line with BUDGET thus
   No solution is possible because of one of the following reasons:
   (1) the given budget of ********.** is insufficient
   (2) one or more MOE requirement level is too high
   (3) cost values are too high and needs to be scaled down.
```

```
      stop
   always

   if ( ( SLOPE1 = SLOPE2 ) and ( L1 = L2 ) )
      skip 1 line
      print 1 line thus
   The cost values are too high for computation & should be scaled down.
      stop
   always

   '' Intercept of the line segments at lamda1 & lamda2 yields lamda3.
   LAMDA3 = ( SUM.LCE.1 - SUM.LCE.2 ) / ( SUM.LCC.1 - SUM.LCC.2 )

   LAMDA = LAMDA3
   call BEST.PATH
   call SUM.LCC.LCE
   SLOPE3 = -1 * ( SUM.LCC - BUDGET )
   L3 = SUM.LCE - LAMDA3 * ( SUM.LCC - BUDGET )

   print 1 line with LAMDA1, LAMDA3, LAMDA2, SLOPE1, SLOPE3, SLOPE2,
      L1, L3, L2 thus
***.*** ****.*** ****.***  ****.** ****.** ****.**  ****.* ****.* ****.*

   '' The minima of the piece-wise linear Lagrangian function L
   '' is reached, ie. the solution is found, when the intercept
   '' lamda3 is equal to any of the two bounds
   if ( LAMDA3 = LAMDA2 )    '' Minima is found & slope there is positive
      return                 '' ie. minima itself  he optimal solution
   always
   if ( LAMDA3 = LAMDA1 )    '' Minima is found but slope is negative.
      LAMDA = LAMDA2         '' Lamda lies on the solution line segment,
      call BEST.PATH         '' which is the one with positive slope next
      call SUM.LCC.LCE       '' to the minima.
      SLOPE3 = -1 * ( SUM.LCC - BUDGET )
      L3 = SUM.LCE - LAMDA3 * ( SUM.LCC - BUDGET )
      print 1 line with LAMDA1, LAMDA3, LAMDA2, SLOPE1, SLOPE3, SLOPE2,
         L1, L3, L2 thus
***.*** ****.*** ****.***  ****.** ****.** ****.**  ****.* ****.* ****.*
      return
   always

   '' Lamda3 replaces the redundant bound for the next iteration.
   if ( SLOPE3 >= 0 )
      let LAMDA2 = LAMDA3
   else
      let LAMDA1 = LAMDA3
   always

   go to 'Iterate'

end
```

```
routine BEST.PATH

   '' Forward dynamic programming with criteria function dependent on
   '' the given approach. Provisions are made to ensure that the solu-
   '' tion path has sufficient lead time for each alternative chosen.

   CRIT.FUNC(1) = 0
   for I = 2 to N.NODE            '' Initialising crit. func. with a very
      CRIT.FUNC(I) = -99999999    '' low value as 0 is too high a default
                                  '' value to prevent adverse selections.
   for I = 2 to N.NODE
   do
      MAX.CF = -999999999
      for J = EP(I) to (EP(I+1)-1)
      do
         '' Lagrangian relaxation approach to obtain the
         '' max. eff. for the given budget.
         if ( APPROACH = "Lagrangian" )
            if ( LCC(J) < 9999999 )
               L(J) = ( LCE(J) - LAMDA * LCC(J) )
            else
               L(J) = -9999999
            always
         always

         '' The approach of maximising the cost-eff.
         '' ratio while meeting given requirements for
         '' effectiveness. The budget is ignored.
         if ( APPROACH = "Cost-Eff.Ratio" )
            if ( LCC(J) < 9999999 )
               L(J) = LCE(J) / ( LCC(J) - MIN.LCC + 1 )
            else
               L(J) = -9999999
            always
         always

         '' The approach of satisfying effectiveness
         '' requirements at minimum cost.
         '' Yields the lower bound on budget.
         if ( APPROACH = "Satisficing" )
            L(J) = -1 * LCC(J)
         always

         '' The approach of maximising effectiveness without
         '' concern for budget. Yields the upper bound on budget.
         if ( APPROACH = "Max.Eff." )
            if ( LCC(J) < 9999999 )
               L(J) = LCE(J)
            else
               L(J) = -9999999
            always
         always

         '' Preventing the selection of an arc that cannot
         '' be used because of insufficient lead time.
```

```
         if ( ALT.CODE(J) > 0 )
            if ( BEST.PRED.NODE(TAIL(J)) = 0 )
               L(J) = -9999999
            else
               K = TRANS.YEAR(TAIL(J)) -
                   TRANS.YEAR(BEST.PRED.NODE(TAIL(J)))
               if ( K < LEAD.TIME(ALT.CODE(J)) )
                  L(J) = -9999999
               always
            always
         always

         if ( CRIT.FUNC(TAIL(J)) > -9999999 )
            if ( CRIT.FUNC(TAIL(J)) + L(J) ) > MAX.CF
               MAX.CF = CRIT.FUNC(TAIL(J)) + L(J)
               CRIT.FUNC(I) = MAX.CF
               BEST.PRED.NODE(I) = TAIL(J)
               BEST.PRED.ARC(I) = J
            always
         always

      loop
   loop

   '' The terminal node with the highest value in the
   '' criteria function yields the solution path that
   '' is optimal for the given approach.
   MAX.CF = -999999999
   MAX.MAC = -999999999
   MAX.AAC = -999999999
   for I = 1 to N.NODE
      with SYS.CODE(I) = SYS.CODE(N.NODE)
      do
         if ( APPROACH = "Satisficing" )
            N = TRANS.YEAR(I) - CURR.YEAR + 1
            INT.DF = ( ( INT.RATE / 100 ) + 1 ) ** ( N - 1 )
            AAC.CF = ( INT.DF * (INT.RATE/100) ) / ( INT.DF - 1 )
            if ( ( CRIT.FUNC(I) / N ) > MAX.MAC )
               MAX.MAC = CRIT.FUNC(I) / N
               ARG.MAC = I
            always
            if ( ( CRIT.FUNC(I) * AAC.CF ) > MAX.AAC )
               MAX.AAC = CRIT.FUNC(I) * AAC.CF
               ARG.AAC = I
            always
         always
         if ( CRIT.FUNC(I) >= MAX.CF )
            MAX.CF = CRIT.FUNC(I)
            ARGMAX.CF = I
         always
      loop

   return

end
```

```
routine SUM.LCC.LCE

   '' Totals up the life-cycle cost & effectiveness
   '' for the solution path.

   I = ARGMAX.CF
   SUM.LCC = 0
   SUM.LCE = 0
   until I = 1
   do
      if ( BEST.PRED.ARC(I) = 0 )
         print 2 lines thus
All paths violates either lead time or MOE level requirements
or both. No feasible solution can be found.
         stop
      always
      SUM.LCC = SUM.LCC + LCC(BEST.PRED.ARC(I))
      SUM.LCE = SUM.LCE + LCE(BEST.PRED.ARC(I))
      I = BEST.PRED.NODE(I)
   loop

   return

end
```

```
routine RESULTS.PRINT

   '' Print-Out of Results

   skip 1 line
   print 6 line thus
Network of Possible Solutions in Nodal Form

Note - The criterion function of a node will be very low if all paths
leading to it fail to satisfy lead time req. and/or minimum MOE levels.

 No.  Sys.  Year  EP  Crit.Fn.  Best.Pred.Node  Best.Pred.Arc  Best.Alt.
   skip 1 line
   print 1 line with SYS.CODE(1), TRANS.YEAR(1), EP(1) and
      CRIT.FUNC(1) thus
   1  ***   **    *   ****.***
   for I = 2 to N.NODE
      print 1 line with I, SYS.CODE(I), TRANS.YEAR(I), EP(I),
         CRIT.FUNC(I), BEST.PRED.NODE(I), BEST.PRED.ARC(I) and
         ALT.CODE(max.f(1,BEST.PRED.ARC(I))) thus
 ***  ***   **    *   ****.***      ***              ***          ***

   if ( CRIT.FUNC(ARGMAX.CF) <= -99999 )
      print 1 line thus
Warning : Lead-time requirements cannot be met.
   always

   if ( SUM.LCC >= 9999999 )
      print 1 line thus
Warning : Minimum MOE level requirements cannot be met.
   always

   if ( APPROACH = "Satisficing" )  '' There are two possible solutions
      skip 1 line                   '' for the satisficing approach.
      print 2 line thus
Minimum Average Annual Cost Solution Path
( Time value of money is ignored, ie. interest rate is assumed to be 0 )
      skip 1 line
      print 2 line thus
     Transition          Alternative  Life-Cycle  Life-Cycle    Criterion
Node    Year    System    Employed       Cost    Effectiveness  Func.Value
      skip 1 line
      I = ARG.MAC
      until I = 1
      do
         print 1 line with I, TRANS.YEAR(I), SYS.CODE(I),
            ALT.CODE(BEST.PRED.ARC(I)), LCC(BEST.PRED.ARC(I)),
            LCE(BEST.PRED.ARC(I)), CRIT.FUNC(I) thus
 ***      **       *         ***      *****.***     *****.***    *****.***
         I = BEST.PRED.NODE(I)
      loop
      skip 1 line
      print 2 line with INT.RATE thus
Minimum Annualised Cost Solution Path
( Monetary interest assumed constant at ***.*** % per annum )
```

```
      skip 1 line
      print 2 line thus
     Transition         Alternative  Life-Cycle  Life-Cycle    Criterion
Node     Year    System   Employed      Cost    Effectiveness  Func.Value
      skip 1 line
      I = ARG.AAC
      until I = 1
      do
         print 1 line with I, TRANS.YEAR(I), SYS.CODE(I),
            ALT.CODE(BEST.PRED.ARC(I)), LCC(BEST.PRED.ARC(I)),
            LCE(BEST.PRED.ARC(I)), CRIT.FUNC(I) thus
 ***     **      *        ***      *****.***     *****.***     *****.***
         I = BEST.PRED.NODE(I)
      loop
      return
   always

   skip 1 line
   print 4 line thus
Solution Path

     Transition         Alternative  Life-Cycle  Life-Cycle    Criterion
Node     Year    System   Employed      Cost    Effectiveness  Func.Value

   skip 1 line
   I = ARGMAX.CF
   until I = 1
   do
      print 1 line with I, TRANS.YEAR(I), SYS.CODE(I),
         ALT.CODE(BEST.PRED.ARC(I)), LCC(BEST.PRED.ARC(I)),
         LCE(BEST.PRED.ARC(I)), CRIT.FUNC(I) thus
 ***     **      *        ***      *****.***     *****.***     *****.***
      I = BEST.PRED.NODE(I)
   loop

   skip 1 line
   if ( ( CRIT.FUNC(ARGMAX.CF) > -99999 ) and ( SUM.LCC < 9999999 ) )
      print 2 line with SUM.LCC and SUM.LCE thus
The total life-cycle cost and effectiveness for the optimal solution
are *******.** and ******.*** respectively.
   always

   skip 1 line
   if ( APPROACH = "Lagrangian" )
      print 1 line with LAMDA3 thus
   Optimal value of the Lagrangian multiplier is *****.*****
      skip 1 line
   always

return

end
```

APPENDIX B: SAMPLE INPUT FILES

```
Stationary.Environment
3 2 3 1989 0
Off
0 5
5 10
5 10
Alt.A  0
Alt.B  0

1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1

Lagrangian
1200
    30 1.3 7 .05 0 0 20 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2
100 30 1.3 7 .05 0 0 50 -.2

300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
```

```
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2
300 15 1.3 4 .05 0 0 90 -.2

Range(nm)        0.4 104.6   -.03
Accuracy(%)      0.3  87.2   -.02
Availability(%) 0.3  93.5   -.03

95 95 95 95 95 95 95 95 95 95 95 95 95
95 95 95 95 95 95 95 95 95 95 95 95 95

80 80 80 80 80 80 80 80 80 80 80 80 80
80 80 80 80 80 80 80 80 80 80 80 80 80

70 70 70 70 70 70 70 70 70 70 70 70 70
70 70 70 70 70 70 70 70 70 70 70 70 70

120 -.03 120 -.03 120 -.03 120 -.03 120 -.03 120 -.03
120 -.03 120 -.03 120 -.03 120 -.03 120 -.03 120 -.03
120 -.03 120 -.03 120 -.03 120 -.03 120 -.03 120 -.03
120 -.03 120 -.03 120 -.03 120 -.03 120 -.03 120 -.03
120 -.03 120 -.03

95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02

95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03

140 -.03 140 -.03 140 -.03 140 -.03 140 -.03 140 -.03
140 -.03 140 -.03 140 -.03 140 -.03 140 -.03 140 -.03
140 -.03 140 -.03 140 -.03 140 -.03 140 -.03 140 -.03
140 -.03 140 -.03 140 -.03 140 -.03 140 -.03 140 -.03
140 -.03 140 -.03

95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02

95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03
```

```
Inflation.&.Interest.Rates
3 2 3 1989 5
Off
0 5
5 10
5 10
Alt.A  0
Alt.B  0

.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95

Satisficing
900
      30.0 1.3  7.0 .05 0 0  20    -.2
100.0 31.2 1.3  7.3 .05 0 0  50.0 -.2
104.0 32.4 1.3  7.6 .05 0 0  52.0 -.2
108.2 33.7 1.3  7.9 .05 0 0  54.1 -.2
112.5 35.1 1.3  8.2 .05 0 0  56.2 -.2
117.0 36.5 1.3  8.5 .05 0 0  58.5 -.2
121.7 38.0 1.3  8.9 .05 0 0  60.8 -.2
126.5 39.5 1.3  9.2 .05 0 0  63.2 -.2
131.6 41.1 1.3  9.6 .05 0 0  65.8 -.2
136.9 42.7 1.3 10.0 .05 0 0  68.4 -.2
142.3 44.4 1.3 10.4 .05 0 0  71.2 -.2
148.0 46.2 1.3 10.8 .05 0 0  74.0 -.2
153.9 48.0 1.3 11.2 .05 0 0  77.0 -.2
160.1 50.0 1.3 11.7 .05 0 0  80.1 -.2
166.5 52.0 1.3 12.1 .05 0 0  83.3 -.2
173.2 54.0 1.3 12.6 .05 0 0  86.6 -.2
180.1 56.2 1.3 13.1 .05 0 0  90.0 -.2
187.3 58.4 1.3 13.6 .05 0 0  93.6 -.2
194.8 60.8 1.3 14.2 .05 0 0  97.4 -.2
202.6 63.2 1.3 14.7 .05 0 0 101.3 -.2
210.7 65.7 1.3 15.3 .05 0 0 105.3 -.2
219.1 68.4 1.3 16.0 .05 0 0 109.6 -.2
227.9 71.1 1.3 16.6 .05 0 0 113.9 -.2
237.0 73.9 1.3 17.2 .05 0 0 118.5 -.2
246.5 76.9 1.3 17.9 .05 0 0 123.2 -.2
256.3 80.0 1.3 18.7 .05 0 0 128.2 -.2
266.5 83.2 1.3 19.4 .05 0 0 133.3 -.2

300.0 15.6 1.3  4.2 .05 0 0  90.0 -.2
312.0 16.2 1.3  4.3 .05 0 0  93.6 -.2
324.5 16.9 1.3  4.5 .05 0 0  97.3 -.2
337.5 17.5 1.3  4.7 .05 0 0 101.2 -.2
351.0 18.2 1.3  4.9 .05 0 0 105.3 -.2
365.0 19.0 1.3  5.1 .05 0 0 109.5 -.2
379.6 19.7 1.3  5.3 .05 0 0 113.9 -.2
394.8 20.5 1.3  5.5 .05 0 0 118.4 -.2
410.6 21.3 1.3  5.7 .05 0 0 123.2 -.2
427.0 22.2 1.3  5.9 .05 0 0 128.1 -.2
444.1 23.1 1.3  6.2 .05 0 0 133.2 -.2
461.8 24.0 1.3  6.4 .05 0 0 138.6 -.2
480.3 25.0 1.3  6.7 .05 0 0 144.1 -.2
499.5 26.0 1.3  6.9 .05 0 0 149.9 -.2
519.5 27.0 1.3  7.2 .05 0 0 155.9 -.2
```

```
540.3 28.1 1.3  7.5 .05 0 0 162.1 -.2
561.9 29.2 1.3  7.8 .05 0 0 168.6 -.2
584.4 30.4 1.3  8.1 .05 0 0 175.3 -.2
607.7 31.6 1.3  8.4 .05 0 0 182.3 -.2
632.1 32.9 1.3  8.8 .05 0 0 189.6 -.2
657.3 34.2 1.3  9.1 .05 0 0 197.2 -.2
683.6 35.5 1.3  9.5 .05 0 0 205.1 -.2
711.0 37.0 1.3  9.9 .05 0 0 213.3 -.2
739.4 38.4 1.3 10.3 .05 0 0 221.8 -.2
769.0 40.0 1.3 10.7 .05 0 0 230.7 -.2
799.8 41.6 1.3 11.1 .05 0 0 239.9 -.2

Range(nm)        0.4 104.6    -.03
Accuracy(%)      0.3  87.2    -.02
Availability(%)  0.3  93.5    -.03

95 95 95 95 95 95 95 95 95 95 95 95 95
95 95 95 95 95 95 95 95 95 95 95 95 95

80 80 80 80 80 80 80 80 80 80 80 80 80
80 80 80 80 80 80 80 80 80 80 80 80 80

70 70 70 70 70 70 70 70 70 70 70 70 70
70 70 70 70 70 70 70 70 70 70 70 70 70

120 -.03 120 -.03 120 -.03 120 -.03 120 -.03 120 -.03
120 -.03 120 -.03 120 -.03 120 -.03 120 -.03 120 -.03
120 -.03 120 -.03 120 -.03 120 -.03 120 -.03 120 -.03
120 -.03 120 -.03 120 -.03 120 -.03 120 -.03 120 -.03
120 -.03 120 -.03

95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02

95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03

140 -.03 140 -.03 140 -.03 140 -.03 140 -.03 140 -.03
140 -.03 140 -.03 140 -.03 140 -.03 140 -.03 140 -.03
140 -.03 140 -.03 140 -.03 140 -.03 140 -.03 140 -.03
140 -.03 140 -.03 140 -.03 140 -.03 140 -.03 140 -.03
140 -.03 140 -.03

95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02 95 -.02 95 -.02 95 -.02 95 -.02
95 -.02 95 -.02

95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03 95 -.03 95 -.03 95 -.03 95 -.03
95 -.03 95 -.03
```

```
Technological.Change
3 2 3 1989 5
Off
0 5
5 10
5 10
Alt.A  0
Alt.B  0

.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95

Satisficing
650
      30.0 1.3  7.0 .05 0 0  20    -.2
100.0 30.3 1.3  7.3 .05 0 0  50.0 -.2
102.0 30.6 1.3  7.6 .05 0 0  51.0 -.2
104.4 30.9 1.3  7.9 .05 0 0  52.2 -.2
106.1 31.2 1.3  8.2 .05 0 0  53.0 -.2
108.2 31.5 1.3  8.5 .05 0 0  54.1 -.2
110.4 31.8 1.3  8.9 .05 0 0  55.2 -.2
112.6 32.2 1.3  9.2 .05 0 0  56.3 -.2
114.9 32.5 1.3  9.6 .05 0 0  57.4 -.2
117.2 32.8 1.3 10.0 .05 0 0  58.6 -.2
119.5 33.1 1.3 10.4 .05 0 0  59.7 -.2
121.9 33.5 1.3 10.8 .05 0 0  60.9 -.2
124.3 33.8 1.3 11.2 .05 0 0  62.1 -.2
126.8 34.1 1.3 11.7 .05 0 0  63.4 -.2
129.4 34.5 1.3 12.1 .05 0 0  64.7 -.2
131.9 34.8 1.3 12.6 .05 0 0  65.9 -.2
134.6 35.2 1.3 13.1 .05 0 0  67.3 -.2
137.3 35.5 1.3 13.6 .05 0 0  68.6 -.2
140.0 35.9 1.3 14.2 .05 0 0  70.0 -.2
142.8 36.2 1.3 14.7 .05 0 0  71.4 -.2
145.7 36.6 1.3 15.3 .05 0 0  72.8 -.2
148.6 37.0 1.3 16.0 .05 0 0  74.3 -.2
151.6 37.3 1.3 16.6 .05 0 0  75.8 -.2
154.6 37.7 1.3 17.2 .05 0 0  77.3 -.2
157.7 38.1 1.3 17.9 .05 0 0  78.8 -.2
160.8 38.5 1.3 18.7 .05 0 0  80.4 -.2
164.1 38.9 1.3 19.4 .05 0 0  82.0 -.2

300.0 15.6 1.3  4.2 .05 0 0  90.0 -.2
303.0 16.2 1.3  4.3 .05 0 0  90.9 -.2
306.0 16.9 1.3  4.5 .05 0 0  91.8 -.2
309.1 17.5 1.3  4.7 .05 0 0  92.7 -.2
312.2 18.2 1.3  4.9 .05 0 0  93.7 -.2
315.3 19.0 1.3  5.1 .05 0 0  94.6 -.2
318.5 19.7 1.3  5.3 .05 0 0  95.5 -.2
321.6 20.5 1.3  5.5 .05 0 0  96.5 -.2
324.9 21.3 1.3  5.7 .05 0 0  97.5 -.2
328.1 22.2 1.3  5.9 .05 0 0  98.4 -.2
331.4 23.1 1.3  6.2 .05 0 0  99.4 -.2
334.7 24.0 1.3  6.4 .05 0 0 100.4 -.2
338.0 25.0 1.3  6.7 .05 0 0 101.4 -.2
341.4 26.0 1.3  6.9 .05 0 0 102.4 -.2
344.8 27.0 1.3  7.2 .05 0 0 103.5 -.2
```

```
348.3 28.1 1.3  7.5 .05 0 0 104.5 -.2
351.8 29.2 1.3  7.8 .05 0 0 105.5 -.2
355.3 30.4 1.3  8.1 .05 0 0 106.6 -.2
358.8 31.6 1.3  8.4 .05 0 0 107.7 -.2
362.4 32.9 1.3  8.8 .05 0 0 108.7 -.2
366.1 34.2 1.3  9.1 .05 0 0 109.8 -.2
369.7 35.5 1.3  9.5 .05 0 0 110.9 -.2
373.4 37.0 1.3  9.9 .05 0 0 112.0 -.2
377.1 38.4 1.3 10.3 .05 0 0 113.1 -.2
380.9 40.0 1.3 10.7 .05 0 0 114.3 -.2
384.7 41.6 1.3 11.1 .05 0 0 115.4 -.2

Range(nm)         0.4 104.6    -.03
Accuracy(%)       0.3  87.2    -.02
Availability(%)   0.3  93.5    -.03

95 95 95 95 95 95 95 95 95 95 95 95 95
95 95 95 95 95 95 95 95 95 95 95 95 95

80 80 80 80 80 80 80 80 80 80 80 80 80
80 80 80 80 80 80 80 80 80 80 80 80 80

70 70 70 70 70 70 70 70 70 70 70 70 70
70 70 70 70 70 70 70 70 70 70 70 70 70

120 -.03 123 -.03 128 -.03 134 -.03 140 -.03 145 -.03
150 -.03 154 -.03 158 -.03 162 -.03 166 -.03 169 -.03
172 -.03 175 -.03 178 -.03 179 -.03 180 -.03 180 -.03
180 -.03 180 -.03 180 -.03 180 -.03 180 -.03 180 -.03
180 -.03 180 -.03

95.0 -.02 95.1 -.02 95.2 -.02 95.3 -.02 95.4 -.02 95.5 -.02
95.6 -.02 95.7 -.02 95.8 -.02 95.9 -.02 96.0 -.02 96.1 -.02
96.2 -.02 96.3 -.02 96.4 -.02 96.4 -.02 96.5 -.02 96.6 -.02
96.7 -.02 96.7 -.02 96.8 -.02 96.8 -.02 96.9 -.02 96.9 -.02
96.9 -.02 97.0 -.02

95.0 -.03 95.1 -.03 95.2 -.03 95.3 -.03 95.4 -.03 95.5 -.03
95.6 -.03 95.7 -.03 95.8 -.03 95.9 -.03 96.0 -.03 96.1 -.03
96.2 -.03 96.3 -.03 96.4 -.03 96.4 -.03 96.5 -.03 96.6 -.03
96.7 -.03 96.7 -.03 96.8 -.03 96.8 -.03 96.9 -.03 96.9 -.03
96.9 -.03 97.0 -.03

140 -.03 144 -.03 147 -.03 150 -.03 153 -.03 155 -.03
158 -.03 160 -.03 162 -.03 164 -.03 165 -.03 167 -.03
168 -.03 169 -.03 170 -.03 171 -.03 172 -.03 173 -.03
173 -.03 174 -.03 175 -.03 175 -.03 176 -.03 176 -.03
176 -.03 177 -.03

95.0 -.02 95.1 -.02 95.2 -.02 95.3 -.02 95.4 -.02 95.5 -.02
95.6 -.02 95.7 -.02 95.8 -.02 95.9 -.02 96.0 -.02 96.1 -.02
96.2 -.02 96.3 -.02 96.4 -.02 96.4 -.02 96.5 -.02 96.6 -.02
96.7 -.02 96.7 -.02 96.8 -.02 96.8 -.02 96.9 -.02 96.9 -.02
96.9 -.02 97.0 -.02

95.0 -.03 95.1 -.03 95.2 -.03 95.3 -.03 95.4 -.03 95.5 -.03
95.6 -.03 95.7 -.03 95.8 -.03 95.9 -.03 96.0 -.03 96.1 -.03
96.2 -.03 96.3 -.03 96.4 -.03 96.4 -.03 96.5 -.03 96.6 -.03
96.7 -.03 96.7 -.03 96.8 -.03 96.8 -.03 96.9 -.03 96.9 -.03
96.9 -.03 97.0 -.03
```

```
Requirement.Escalation
3 2 3 1989 5
Off
0 5
5 10
5 10
Alt.A  0
Alt.B  0

.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95

Lagrangian
700
      30.0 1.3  7.0 .05 0 0  20    -.2
100.0 30.3 1.3  7.3 .05 0 0  50.0 -.2
102.0 30.6 1.3  7.6 .05 0 0  51.0 -.2
104.4 30.9 1.3  7.9 .05 0 0  52.2 -.2
106.1 31.2 1.3  8.2 .05 0 0  53.0 -.2
108.2 31.5 1.3  8.5 .05 0 0  54.1 -.2
110.4 31.8 1.3  8.9 .05 0 0  55.2 -.2
112.6 32.2 1.3  9.2 .05 0 0  56.3 -.2
114.9 32.5 1.3  9.6 .05 0 0  57.4 -.2
117.2 32.8 1.3 10.0 .05 0 0  58.6 -.2
119.5 33.1 1.3 10.4 .05 0 0  59.7 -.2
121.9 33.5 1.3 10.8 .05 0 0  60.9 -.2
124.3 33.8 1.3 11.2 .05 0 0  62.1 -.2
126.8 34.1 1.3 11.7 .05 0 0  63.4 -.2
129.4 34.5 1.3 12.1 .05 0 0  64.7 -.2
131.9 34.8 1.3 12.6 .05 0 0  65.9 -.2
134.6 35.2 1.3 13.1 .05 0 0  67.3 -.2
137.3 35.5 1.3 13.6 .05 0 0  68.6 -.2
140.0 35.9 1.3 14.2 .05 0 0  70.0 -.2
142.8 36.2 1.3 14.7 .05 0 0  71.4 -.2
145.7 36.6 1.3 15.3 .05 0 0  72.8 -.2
148.6 37.0 1.3 16.0 .05 0 0  74.3 -.2
151.6 37.3 1.3 16.6 .05 0 0  75.8 -.2
154.6 37.7 1.3 17.2 .05 0 0  77.3 -.2
157.7 38.1 1.3 17.9 .05 0 0  78.8 -.2
160.8 38.5 1.3 18.7 .05 0 0  80.4 -.2
164.1 38.9 1.3 19.4 .05 0 0  82.0 -.2

300.0 15.6 1.3  4.2 .05 0 0  90.0 -.2
303.0 16.2 1.3  4.3 .05 0 0  90.9 -.2
306.0 16.9 1.3  4.5 .05 0 0  91.8 -.2
309.1 17.5 1.3  4.7 .05 0 0  92.7 -.2
312.2 18.2 1.3  4.9 .05 0 0  93.7 -.2
315.3 19.0 1.3  5.1 .05 0 0  94.6 -.2
318.5 19.7 1.3  5.3 .05 0 0  95.5 -.2
321.6 20.5 1.3  5.5 .05 0 0  96.5 -.2
324.9 21.3 1.3  5.7 .05 0 0  97.5 -.2
328.1 22.2 1.3  5.9 .05 0 0  98.4 -.2
331.4 23.1 1.3  6.2 .05 0 0  99.4 -.2
334.7 24.0 1.3  6.4 .05 0 0 100.4 -.2
338.0 25.0 1.3  6.7 .05 0 0 101.4 -.2
341.4 26.0 1.3  6.9 .05 0 0 102.4 -.2
344.8 27.0 1.3  7.2 .05 0 0 103.5 -.2
```

```
348.3 28.1 1.3  7.5 .05 0 0 104.5 -.2
351.8 29.2 1.3  7.8 .05 0 0 105.5 -.2
355.3 30.4 1.3  8.1 .05 0 0 106.6 -.2
358.8 31.6 1.3  8.4 .05 0 0 107.7 -.2
362.4 32.9 1.3  8.8 .05 0 0 108.7 -.2
366.1 34.2 1.3  9.1 .05 0 0 109.8 -.2
369.7 35.5 1.3  9.5 .05 0 0 110.9 -.2
373.4 37.0 1.3  9.9 .05 0 0 112.0 -.2
377.1 38.4 1.3 10.3 .05 0 0 113.1 -.2
380.9 40.0 1.3 10.7 .05 0 0 114.3 -.2
384.7 41.6 1.3 11.1 .05 0 0 115.4 -.2

Range(nm)        0.4 104.6   -.03
Accuracy(%)      0.3  87.2   -.02
Availability(%) 0.3  93.5   -.03

 95  95  95 100 100 100 110 110 110 110 110 110 110
110 110 110 110 110 110 110 110 110 110 110 110 110

80 80 80 80 80 80 80 80 80 80 80 80 80
80 80 80 80 80 80 80 80 80 80 80 80 80

70 70 70 72 72 72 72 75 75 75 75 75 75
75 75 75 75 75 75 75 75 75 75 75 75 75

120 -.03 123 -.03 128 -.03 134 -.03 140 -.03 145 -.03
150 -.03 154 -.03 158 -.03 162 -.03 166 -.03 169 -.03
172 -.03 175 -.03 178 -.03 179 -.03 180 -.03 180 -.03
180 -.03 180 -.03 180 -.03 180 -.03 180 -.03 180 -.03
180 -.03 180 -.03

95.0 -.02 95.1 -.02 95.2 -.02 95.3 -.02 95.4 -.02 95.5 -.02
95.6 -.02 95.7 -.02 95.8 -.02 95.9 -.02 96.0 -.02 96.1 -.02
96.2 -.02 96.3 -.02 96.4 -.02 96.4 -.02 96.5 -.02 96.6 -.02
96.7 -.02 96.7 -.02 96.8 -.02 96.8 -.02 96.9 -.02 96.9 -.02
96.9 -.02 97.0 -.02

95.0 -.03 95.1 -.03 95.2 -.03 95.3 -.03 95.4 -.03 95.5 -.03
95.6 -.03 95.7 -.03 95.8 -.03 95.9 -.03 96.0 -.03 96.1 -.03
96.2 -.03 96.3 -.03 96.4 -.03 96.4 -.03 96.5 -.03 96.6 -.03
96.7 -.03 96.7 -.03 96.8 -.03 96.8 -.03 96.9 -.03 96.9 -.03
96.9 -.03 97.0 -.03

140 -.03 144 -.03 147 -.03 150 -.03 153 -.03 155 -.03
158 -.03 160 -.03 162 -.03 164 -.03 165 -.03 167 -.03
168 -.03 169 -.03 170 -.03 171 -.03 172 -.03 173 -.03
173 -.03 174 -.03 175 -.03 175 -.03 176 -.03 176 -.03
176 -.03 177 -.03

95.0 -.02 95.1 -.02 95.2 -.02 95.3 -.02 95.4 -.02 95.5 -.02
95.6 -.02 95.7 -.02 95.8 -.02 95.9 -.02 96.0 -.02 96.1 -.02
96.2 -.02 96.3 -.02 96.4 -.02 96.4 -.02 96.5 -.02 96.6 -.02
96.7 -.02 96.7 -.02 96.8 -.02 96.8 -.02 96.9 -.02 96.9 -.02
96.9 -.02 97.0 -.02

95.0 -.03 95.1 -.03 95.2 -.03 95.3 -.03 95.4 -.03 95.5 -.03
95.6 -.03 95.7 -.03 95.8 -.03 95.9 -.03 96.0 -.03 96.1 -.03
96.2 -.03 96.3 -.03 96.4 -.03 96.4 -.03 96.5 -.03 96.6 -.03
96.7 -.03 96.7 -.03 96.8 -.03 96.8 -.03 96.9 -.03 96.9 -.03
96.9 -.03 97.0 -.03
```

```
Upgrading.Scheduling
3 2 3 1989 5
Off
0 5
5 10
5 10
Alt.A  0
Alt.B  0

.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95

Cost-Eff.Ratio
780.08
      30.0 1.3  7.0 .05 0 0  20   -.2
100.0 30.3 1.3  7.3 .05 0 0  50.0 -.2
 82.0 30.6 1.3  7.6 .05 0 0  51.0 -.2
104.4 30.9 1.3  7.9 .05 0 0  52.2 -.2
106.1 31.2 1.3  8.2 .05 0 0  53.0 -.2
 86.2 31.5 1.3  8.5 .05 0 0  54.1 -.2
110.4 31.8 1.3  8.9 .05 0 0  55.2 -.2
112.6 32.2 1.3  9.2 .05 0 0  56.3 -.2
 90.9 32.5 1.3  9.6 .05 0 0  57.4 -.2
117.2 32.8 1.3 10.0 .05 0 0  58.6 -.2
119.5 33.1 1.3 10.4 .05 0 0  59.7 -.2
 95.9 33.5 1.3 10.8 .05 0 0  60.9 -.2
124.3 33.8 1.3 11.2 .05 0 0  62.1 -.2
126.8 34.1 1.3 11.7 .05 0 0  63.4 -.2
101.4 34.5 1.3 12.1 .05 0 0  64.7 -.2
131.9 34.8 1.3 12.6 .05 0 0  65.9 -.2
134.6 35.2 1.3 13.1 .05 0 0  67.3 -.2
107.3 35.5 1.3 13.6 .05 0 0  68.6 -.2
140.0 35.9 1.3 14.2 .05 0 0  70.0 -.2
142.8 36.2 1.3 14.7 .05 0 0  71.4 -.2
113.7 36.6 1.3 15.3 .05 0 0  72.8 -.2
148.6 37.0 1.3 16.0 .05 0 0  74.3 -.2
151.6 37.3 1.3 16.6 .05 0 0  75.8 -.2
120.6 37.7 1.3 17.2 .05 0 0  77.3 -.2
157.7 38.1 1.3 17.9 .05 0 0  78.8 -.2
160.8 38.5 1.3 18.7 .05 0 0  80.4 -.2
128.1 38.9 1.3 19.4 .05 0 0  82.0 -.2

300.0 15.6 1.3  4.2 .05 0 0  90.0 -.2
303.0 16.2 1.3  4.3 .05 0 0  90.9 -.2
306.0 16.9 1.3  4.5 .05 0 0  91.8 -.2
309.1 17.5 1.3  4.7 .05 0 0  92.7 -.2
312.2 18.2 1.3  4.9 .05 0 0  93.7 -.2
315.3 19.0 1.3  5.1 .05 0 0  94.6 -.2
318.5 19.7 1.3  5.3 .05 0 0  95.5 -.2
321.6 20.5 1.3  5.5 .05 0 0  96.5 -.2
324.9 21.3 1.3  5.7 .05 0 0  97.5 -.2
328.1 22.2 1.3  5.9 .05 0 0  98.4 -.2
331.4 23.1 1.3  6.2 .05 0 0  99.4 -.2
334.7 24.0 1.3  6.4 .05 0 0 100.4 -.2
338.0 25.0 1.3  6.7 .05 0 0 101.4 -.2
341.4 26.0 1.3  6.9 .05 0 0 102.4 -.2
344.8 27.0 1.3  7.2 .05 0 0 103.5 -.2
```

```
348.3 28.1 1.3  7.5 .05 0 0 104.5 -.2
351.8 29.2 1.3  7.8 .05 0 0 105.5 -.2
355.3 30.4 1.3  8.1 .05 0 0 106.6 -.2
358.8 31.6 1.3  8.4 .05 0 0 107.7 -.2
362.4 32.9 1.3  8.8 .05 0 0 108.7 -.2
366.1 34.2 1.3  9.1 .05 0 0 109.8 -.2
369.7 35.5 1.3  9.5 .05 0 0 110.9 -.2
373.4 37.0 1.3  9.9 .05 0 0 112.0 -.2
377.1 38.4 1.3 10.3 .05 0 0 113.1 -.2
380.9 40.0 1.3 10.7 .05 0 0 114.3 -.2
384.7 41.6 1.3 11.1 .05 0 0 115.4 -.2

Range(nm)        0.4 104.6    -.03
Accuracy(%)      0.3  87.2    -.02
Availability(%)  0.3  93.5    -.03

 95  95  95 100 100 100 110 110 110 110 110 110 110
110 110 110 110 110 110 110 110 110 110 110 110 110

80 80 80 80 80 80 80 80 80 80 80 80 80
80 80 80 80 80 80 80 80 80 80 80 80 80

70 70 70 72 72 72 72 75 75 75 75 75 75
75 75 75 75 75 75 75 75 75 75 75 75 75

120 -.03 123 -.03 128 -.03 134 -.03 140 -.03 145 -.03
150 -.03 154 -.03 158 -.03 162 -.03 166 -.03 169 -.03
172 -.03 175 -.03 178 -.03 179 -.03 180 -.03 180 -.03
180 -.03 180 -.03 180 -.03 180 -.03 180 -.03 180 -.03
180 -.03 180 -.03

95.0 -.02 95.1 -.02 95.2 -.02 95.3 -.02 95.4 -.02 95.5 -.02
95.6 -.02 95.7 -.02 95.8 -.02 95.9 -.02 96.0 -.02 96.1 -.02
96.2 -.02 96.3 -.02 96.4 -.02 96.4 -.02 96.5 -.02 96.6 -.02
96.7 -.02 96.7 -.02 96.8 -.02 96.8 -.02 96.9 -.02 96.9 -.02
96.9 -.02 97.0 -.02

95.0 -.03 95.1 -.03 95.2 -.03 95.3 -.03 95.4 -.03 95.5 -.03
95.6 -.03 95.7 -.03 95.8 -.03 95.9 -.03 96.0 -.03 96.1 -.03
96.2 -.03 96.3 -.03 96.4 -.03 96.4 -.03 96.5 -.03 96.6 -.03
96.7 -.03 96.7 -.03 96.8 -.03 96.8 -.03 96.9 -.03 96.9 -.03
96.9 -.03 97.0 -.03

140 -.03 144 -.03 147 -.03 150 -.03 153 -.03 155 -.03
158 -.03 160 -.03 162 -.03 164 -.03 165 -.03 167 -.03
168 -.03 169 -.03 170 -.03 171 -.03 172 -.03 173 -.03
173 -.03 174 -.03 175 -.03 175 -.03 176 -.03 176 -.03
176 -.03 177 -.03

95.0 -.02 95.1 -.02 95.2 -.02 95.3 -.02 95.4 -.02 95.5 -.02
95.6 -.02 95.7 -.02 95.8 -.02 95.9 -.02 96.0 -.02 96.1 -.02
96.2 -.02 96.3 -.02 96.4 -.02 96.4 -.02 96.5 -.02 96.6 -.02
96.7 -.02 96.7 -.02 96.8 -.02 96.8 -.02 96.9 -.02 96.9 -.02
96.9 -.02 97.0 -.02

95.0 -.03 95.1 -.03 95.2 -.03 95.3 -.03 95.4 -.03 95.5 -.03
95.6 -.03 95.7 -.03 95.8 -.03 95.9 -.03 96.0 -.03 96.1 -.03
96.2 -.03 96.3 -.03 96.4 -.03 96.4 -.03 96.5 -.03 96.6 -.03
96.7 -.03 96.7 -.03 96.8 -.03 96.8 -.03 96.9 -.03 96.9 -.03
96.9 -.03 97.0 -.03
```

```
Development.Lead.Time
3 2 3 1989 5
On
0 5
5 10
5 10
Alt.A  1
Alt.B  0

.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95 .95 .95 .95 .95
.95 .95

Lagrangian
634.52
      30.0 1.3  7.0 .05 0 0  20    -.2
100.0 30.3 1.3  7.3 .05 0 0  50.0 -.2
 82.0 30.6 1.3  7.6 .05 0 0  51.0 -.2
104.4 30.9 1.3  7.9 .05 0 0  52.2 -.2
106.1 31.2 1.3  8.2 .05 0 0  53.0 -.2
 86.2 31.5 1.3  8.5 .05 0 0  54.1 -.2
110.4 31.8 1.3  8.9 .05 0 0  55.2 -.2
112.6 32.2 1.3  9.2 .05 0 0  56.3 -.2
 90.9 32.5 1.3  9.6 .05 0 0  57.4 -.2
117.2 32.8 1.3 10.0 .05 0 0  58.6 -.2
119.5 33.1 1.3 10.4 .05 0 0  59.7 -.2
 95.9 33.5 1.3 10.8 .05 0 0  60.9 -.2
124.3 33.8 1.3 11.2 .05 0 0  62.1 -.2
126.8 34.1 1.3 11.7 .05 0 0  63.4 -.2
101.4 34.5 1.3 12.1 .05 0 0  64.7 -.2
131.9 34.8 1.3 12.6 .05 0 0  65.9 -.2
134.6 35.2 1.3 13.1 .05 0 0  67.3 -.2
107.3 35.5 1.3 13.6 .05 0 0  68.6 -.2
140.0 35.9 1.3 14.2 .05 0 0  70.0 -.2
142.8 36.2 1.3 14.7 .05 0 0  71.4 -.2
113.7 36.6 1.3 15.3 .05 0 0  72.8 -.2
148.6 37.0 1.3 16.0 .05 0 0  74.3 -.2
151.6 37.3 1.3 16.6 .05 0 0  75.8 -.2
120.6 37.7 1.3 17.2 .05 0 0  77.3 -.2
157.7 38.1 1.3 17.9 .05 0 0  78.8 -.2
160.8 38.5 1.3 18.7 .05 0 0  80.4 -.2
128.1 38.9 1.3 19.4 .05 0 0  82.0 -.2

300.0 15.6 1.3  4.2 .05 0 0  90.0 -.2
303.0 16.2 1.3  4.3 .05 0 0  90.9 -.2
306.0 16.9 1.3  4.5 .05 0 0  91.8 -.2
309.1 17.5 1.3  4.7 .05 0 0  92.7 -.2
312.2 18.2 1.3  4.9 .05 0 0  93.7 -.2
315.3 19.0 1.3  5.1 .05 0 0  94.6 -.2
318.5 19.7 1.3  5.3 .05 0 0  95.5 -.2
321.6 20.5 1.3  5.5 .05 0 0  96.5 -.2
324.9 21.3 1.3  5.7 .05 0 0  97.5 -.2
328.1 22.2 1.3  5.9 .05 0 0  98.4 -.2
331.4 23.1 1.3  6.2 .05 0 0  99.4 -.2
334.7 24.0 1.3  6.4 .05 0 0 100.4 -.2
338.0 25.0 1.3  6.7 .05 0 0 101.4 -.2
341.4 26.0 1.3  6.9 .05 0 0 102.4 -.2
344.8 27.0 1.3  7.2 .05 0 0 103.5 -.2
```

```
348.3 28.1 1.3  7.5 .05 0 0 104.5 -.2
351.8 29.2 1.3  7.8 .05 0 0 105.5 -.2
355.3 30.4 1.3  8.1 .05 0 0 106.6 -.2
358.8 31.6 1.3  8.4 .05 0 0 107.7 -.2
362.4 32.9 1.3  8.8 .05 0 0 108.7 -.2
366.1 34.2 1.3  9.1 .05 0 0 109.8 -.2
369.7 35.5 1.3  9.5 .05 0 0 110.9 -.2
373.4 37.0 1.3  9.9 .05 0 0 112.0 -.2
377.1 38.4 1.3 10.3 .05 0 0 113.1 -.2
380.9 40.0 1.3 10.7 .05 0 0 114.3 -.2
384.7 41.6 1.3 11.1 .05 0 0 115.4 -.2

Range(nm)        0.4 104.6    -.03
Accuracy(%)      0.3  87.2    -.02
Availability(%)  0.3  93.5    -.03

 95  95  95 100 100 100 110 110 110 110 110 110 110
110 110 110 110 110 110 110 110 110 110 110 110 110

80 80 80 80 80 80 80 80 80 80 80 80 80
80 80 80 80 80 80 80 80 80 80 80 80 80

70 70 70 72 72 72 72 75 75 75 75 75 75
75 75 75 75 75 75 75 75 75 75 75 75 75

120 -.03 123 -.03 128 -.03 134 -.03 140 -.03 145 -.03
150 -.03 154 -.03 158 -.03 162 -.03 166 -.03 169 -.03
172 -.03 175 -.03 178 -.03 179 -.03 180 -.03 180 -.03
180 -.03 180 -.03 180 -.03 180 -.03 180 -.03 180 -.03
180 -.03 180 -.03

95.0 -.02 95.1 -.02 95.2 -.02 95.3 -.02 95.4 -.02 95.5 -.02
95.6 -.02 95.7 -.02 95.8 -.02 95.9 -.02 96.0 -.02 96.1 -.02
96.2 -.02 96.3 -.02 96.4 -.02 96.4 -.02 96.5 -.02 96.6 -.02
96.7 -.02 96.7 -.02 96.8 -.02 96.8 -.02 96.9 -.02 96.9 -.02
96.9 -.02 97.0 -.02

95.0 -.03 95.1 -.03 95.2 -.03 95.3 -.03 95.4 -.03 95.5 -.03
95.6 -.03 95.7 -.03 95.8 -.03 95.9 -.03 96.0 -.03 96.1 -.03
96.2 -.03 96.3 -.03 96.4 -.03 96.4 -.03 96.5 -.03 96.6 -.03
96.7 -.03 96.7 -.03 96.8 -.03 96.8 -.03 96.9 -.03 96.9 -.03
96.9 -.03 97.0 -.03

140 -.03 144 -.03 147 -.03 150 -.03 153 -.03 155 -.03
158 -.03 160 -.03 162 -.03 164 -.03 165 -.03 167 -.03
168 -.03 169 -.03 170 -.03 171 -.03 172 -.03 173 -.03
173 -.03 174 -.03 175 -.03 175 -.03 176 -.03 176 -.03
176 -.03 177 -.03

95.0 -.02 95.1 -.02 95.2 -.02 95.3 -.02 95.4 -.02 95.5 -.02
95.6 -.02 95.7 -.02 95.8 -.02 95.9 -.02 96.0 -.02 96.1 -.02
96.2 -.02 96.3 -.02 96.4 -.02 96.4 -.02 96.5 -.02 96.6 -.02
96.7 -.02 96.7 -.02 96.8 -.02 96.8 -.02 96.9 -.02 96.9 -.02
96.9 -.02 97.0 -.02

95.0 -.03 95.1 -.03 95.2 -.03 95.3 -.03 95.4 -.03 95.5 -.03
95.6 -.03 95.7 -.03 95.8 -.03 95.9 -.03 96.0 -.03 96.1 -.03
96.2 -.03 96.3 -.03 96.4 -.03 96.4 -.03 96.5 -.03 96.6 -.03
96.7 -.03 96.7 -.03 96.8 -.03 96.8 -.03 96.9 -.03 96.9 -.03
96.9 -.03 97.0 -.03
```

APPENDIX C: SAMPLE OUTPUT FILES

Dynamic End-Of-Life-Cycle Planning Model

Case of Technological Change

Approach - Lagrangian   Budget = $ 601.74

Note : Budget is used only for the Lagrangian relaxation approach and is ignored in the other approaches.

Iterations of the Lagrangian Relaxation Method

Lamda1	Lamda3	Lamda2	Slope1	Slope3	Slope2	L1	L3	L2
0.	.025	2.080	-306.09	-32.79	27.04	18.8	11.4	66.7
.025	.029	2.080	-32.79	-.01	27.04	11.4	11.4	66.7
.029	.032	2.080	-.01	27.04	27.04	11.4	11.4	66.7
.029	.032	.032	-.01	27.04	27.04	11.4	11.4	11.4

Network of Possible Solutions in Nodal Form

Note - The criterion function of a node will be very low if all paths leading to it fail to satisfy lead time req. and/or minimum MOE levels.

No.	Sys.	Year	EP	Crit.Fn.	Best.Pred.Node	Best.Pred.Arc	Best.Alt.
1	0	1989	0	0.			
2	1	1989	1	1.411	1	1	0
3	1	1990	2	.649	1	2	0
4	1	1991	3	-.311	1	3	0
5	1	1992	4	-1.374	1	4	0
6	1	1993	5	-1.000E+007	1	5	0
7	1	1994	6	-1.000E+007	1	6	0
8	2	1994	7	-4.107	2	7	1
9	2	1995	9	-4.476	3	11	1
10	2	1996	13	-5.013	4	17	1
11	2	1997	19	-5.659	5	25	1
12	2	1998	27	-6.302	5	33	1
13	2	1999	37	-6.876	5	43	1
14	2	2000	49	-7.378	5	53	1
15	2	2001	59	-1.000E+007	4	60	2
16	2	2002	67	-1.000E+007	5	67	1
17	2	2003	73	-1.000E+008	0	0	0
18	2	2004	77	-1.000E+008	0	0	0
19	3	1999	79	-7.772	8	79	1
20	3	2000	81	-7.772	9	83	1
21	3	2001	85	-7.962	10	89	1
22	3	2002	91	-8.285	11	97	1
23	3	2003	99	-8.598	12	107	1
24	3	2004	109	-8.860	13	119	1
25	3	2005	121	-9.075	14	131	1
26	3	2006	133	-9.316	14	141	1
27	3	2007	145	-9.510	14	151	1
28	3	2008	157	-9.657	14	161	1
29	3	2009	169	-9.755	14	171	1
30	3	2010	181	-1.000E+007	14	182	2

31	3	2011	191-1.000E+008	15	191	1
32	3	2012	199-1.000E+008	16	199	1
33	3	2013	205-1.000E+008	0	0	0
34	3	2014	209-1.000E+008	0	0	0

Solution Path

Node	Transition Year	System	Alternative Employed	Life-Cycle Cost	Life-Cycle Effectiveness	Criterion Func.Value
19	1999	3	1	273.366	5.029	-7.772
8	1994	2	1	321.339	4.702	-4.107
2	1989	1	0	-20.000	.775	1.411

The total life-cycle cost and effectiveness for the optimal solution are 574.70 and 10.506 respectively.

Optimal value of the Lagrangian multiplier is .03180

Dynamic End-Of-Life-Cycle Planning Model

Case of Upgrading.Scheduling

Approach - Satisficing   Budget = $ 780.08

Note : Budget is used only for the Lagrangian relaxation approach and is ignored in the other approaches.

Sys.Code	Min.Life	Max.Life	Base.Yr.	No.Nodes	No.Arcs
1	0	5	1989	6	6
2	5	10	1994	11	72
3	5	10	1999	16	132

Alternative Name	Alt.Code	Lead Time
Alt.A	1	0
Alt.B	2	0

Code	Measure of Effectiveness Name	Weightage	Present System Level	Exp.RateOfChange
1	Range(nm)	.400	104.600	-.030
2	Accuracy(%)	.300	87.200	-.020
3	Availability(%)	.300	93.500	-.030

Candidate Arcs For Solution Path

Note - LCC is made to be unfavorably high if the minimum requirement level for any component MOE of LCE has not been met. The limiting MOE is given as the highest index of the MOE(s) that failed to meet the minimum requirement level(s) during the life-span covered by the arc.

Arc No.	Alt. Code	Tail Node	Head Node	Life-Cycle Effectiveness	Cost	Limiting MOE
1	0	1	2	.7745	-20.00	0
2	0	1	3	1.5287	27.67	0
3	0	1	4	2.2632	80.95	0
4	0	1	5	2.9783	9999999.00	1
5	0	1	6	3.6748	9999999.00	1
6	0	1	7	4.3530	9999999.00	2
7	1	2	8	4.7024	302.34	0
8	2	2	8	4.9501	385.58	0
9	1	2	9	5.4160	9999999.00	1
10	2	2	9	5.7008	415.63	0
11	1	3	9	4.7430	9999999.00	1
12	2	3	9	5.0031	374.09	0
13	1	2	10	6.1109	9999999.00	1
14	2	2	10	6.4318	443.29	0
15	1	3	10	5.4626	9999999.00	1
16	2	3	10	5.7617	403.70	0
17	1	4	10	4.8083	299.01	0
18	2	4	10	5.0436	362.25	0
19	1	2	11	6.7877	9999999.00	3
20	2	2	11	7.1436	9999999.00	3
21	1	3	11	6.1635	9999999.00	1

22	2	3	11	6.5004	430.97	0
23	1	4	11	5.53779999999.00		1
24	2	4	11	5.8083	391.28	0
25	1	5	11	4.8860	270.43	0
26	2	5	11	5.0842	351.22	0
27	1	2	12	7.44699999999.00		3
28	2	2	12	7.83679999999.00		3
29	1	3	12	6.84609999999.00		3
30	2	3	12	7.21969999999.00		3
31	1	4	12	6.24819999999.00		1
32	2	4	12	6.5529	418.01	0
33	1	5	12	5.6271	313.96	0
34	2	5	12	5.8550	379.75	0
35	1	6	12	4.9637	278.45	0
36	2	6	12	5.1247	340.96	0
37	1	2	13	8.08899999999.00		3
38	2	2	13	8.51169999999.00		3
39	1	3	13	7.51089999999.00		3
40	2	3	13	7.92009999999.00		3
41	1	4	13	6.93999999999.00		3
42	2	4	13	7.27799999999.00		3
43	1	5	13	6.34879999999.00		1
44	2	5	13	6.6054	406.06	0
45	1	6	13	5.7164	320.43	0
46	2	6	13	5.9016	369.09	0
47	1	7	13	5.0290	269.00	0
48	2	7	13	5.1529	330.40	0
49	1	3	14	8.15829999999.00		3
50	2	3	14	8.60209999999.00		3
51	1	4	14	7.61369999999.00		3
52	2	4	14	7.98389999999.00		3
53	1	5	14	7.05159999999.00		3
54	2	5	14	7.33629999999.00		3
55	1	6	14	6.4494	359.70	0
56	2	6	14	6.6580	395.03	0
57	1	7	14	5.7915	309.51	0
58	2	7	14	5.9340	357.99	0
59	1	4	15	8.26979999999.00		3
60	2	4	15	8.67139999999.00		3
61	1	5	15	7.73599999999.00		3
62	2	5	15	8.04779999999.00		3
63	1	6	15	7.1632	396.23	0
64	2	6	15	7.3944	418.86	0
65	1	7	15	6.5340	347.41	0
66	2	7	15	6.6945	383.44	0
67	1	5	16	8.40249999999.00		3
68	2	5	16	8.74059999999.00		3
69	1	6	16	7.85829999999.00		3
70	2	6	16	8.11159999999.00		3
71	1	7	16	7.2570	382.67	0
72	2	7	16	7.4349	406.84	0
73	1	6	17	8.53509999999.00		3
74	2	6	17	8.80989999999.00		3
75	1	7	17	7.96109999999.00		3
76	2	7	17	8.15599999999.00		3

77	1	7	18	8.6465	9999.00	3
78	2	7	18	8.8579	9999.00	3
79	1	8	19	5.0290	255.72	0
80	2	8	19	5.1529	337.32	0
81	1	8	20	5.7915	296.82	0
82	2	8	20	5.9340	365.87	0
83	1	9	20	5.0943	263.82	0
84	2	9	20	5.1934	327.16	0
85	1	8	21	6.5340	335.28	0
86	2	8	21	6.6945	392.24	0
87	1	9	21	5.8667	303.43	0
88	2	9	21	5.9806	355.21	0
89	1	10	21	5.1472	254.57	0
90	2	10	21	5.2216	317.61	0
91	1	8	22	7.2570	371.05	0
92	2	8	22	7.4349	416.48	0
93	1	9	22	6.6187	340.50	0
94	2	9	22	6.7470	381.12	0
95	1	10	22	5.9275	292.74	0
96	2	10	22	6.0130	345.21	0
97	1	11	22	5.2002	229.69	0
98	2	11	22	5.2497	308.53	0
99	1	8	23	7.9610	9999.00	3
100	2	8	23	8.1559	9999.00	3
101	1	9	23	7.3509	374.97	0
102	2	9	23	7.4932	404.96	0
103	1	10	23	6.6872	328.45	0
104	2	10	23	6.7835	370.73	0
105	1	11	23	5.9884	266.54	0
106	2	11	23	6.0454	335.72	0
107	1	12	23	5.2531	237.36	0
108	2	12	23	5.2779	299.28	0
109	1	8	24	8.6465	9999.00	3
110	2	8	24	8.8579	9999.00	3
111	1	9	24	8.0638	9999.00	3
112	2	9	24	8.2197	9999.00	3
113	1	10	24	7.4269	361.66	0
114	2	10	24	7.5337	394.22	0
115	1	11	24	6.7558	301.03	0
116	2	11	24	6.8200	360.88	0
117	1	12	24	6.0493	272.86	0
118	2	12	24	6.0778	325.99	0
119	1	13	24	5.3060	229.22	0
120	2	13	24	5.2936	290.87	0
121	1	9	25	8.7580	9999.00	3
122	2	9	25	8.9271	9999.00	3
123	1	10	25	8.1472	9999.00	3
124	2	10	25	8.2641	9999.00	3
125	1	11	25	7.5030	333.10	0
126	2	11	25	7.5742	384.04	0
127	1	12	25	6.8244	306.08	0
128	2	12	25	6.8565	350.70	0
129	1	13	25	6.1101	263.45	0
130	2	13	25	6.0959	317.19	0
131	1	14	25	5.3466	206.34	0

132	2	14	25	5.3218	282.34	0
133	1	10	26	8.84849999999.00		3
134	2	10	26	8.97529999999.00		3
135	1	11	26	8.23059999999.00		3
136	2	11	26	8.30849999999.00		3
137	1	12	26	7.5791	336.97	0
138	2	12	26	7.6146	373.47	0
139	1	13	26	6.8930	295.48	0
140	2	13	26	6.8769	341.56	0
141	1	14	26	6.1568	239.38	0
142	2	14	26	6.1283	308.21	0
143	1	15	26	5.3871	213.78	0
144	2	15	26	5.3376	274.17	0
145	1	11	27	8.93889999999.00		3
146	2	11	27	9.02339999999.00		3
147	1	12	27	8.31389999999.00		3
148	2	12	27	8.35289999999.00		3
149	1	13	27	7.6551	325.27	0
150	2	13	27	7.6373	364.02	0
151	1	14	27	6.9455	270.30	0
152	2	14	27	6.9134	332.17	0
153	1	15	27	6.2034	245.62	0
154	2	15	27	6.1464	299.60	0
155	1	16	27	5.4277	206.71	0
156	2	16	27	5.3533	266.52	0
157	1	12	28	9.02929999999.00		3
158	2	12	28	9.07159999999.00		3
159	1	13	28	8.39719999999.00		3
160	2	13	28	8.37779999999.00		3
161	1	14	28	7.7134	299.05	0
162	2	14	28	7.6778	354.26	0
163	1	15	28	6.9981	275.42	0
164	2	15	28	6.9339	323.17	0
165	1	16	28	6.2500	237.47	0
166	2	16	28	6.1646	291.56	0
167	1	17	28	5.4682	185.59	0
168	2	17	28	5.3691	258.95	0
169	1	13	29	9.11969999999.00		3
170	2	13	29	9.09849999999.00		3
171	1	14	29	8.46109999999.00		3
172	2	14	29	8.42209999999.00		3
173	1	15	29	7.7717	303.13	0
174	2	15	29	7.7005	344.91	0
175	1	16	29	7.0506	266.25	0
176	2	16	29	6.9543	314.78	0
177	1	17	29	6.2967	215.24	0
178	2	17	29	6.1827	283.58	0
179	1	18	29	5.4806	192.99	0
180	2	18	29	5.3815	251.77	0
181	1	14	30	9.18889999999.00		3
182	2	14	30	9.14669999999.00		3
183	1	15	30	8.52489999999.00		3
184	2	15	30	8.44699999999.00		3
185	1	16	30	7.8299	293.02	0
186	2	16	30	7.7232	336.21	0

187	1	17	30	7.1031	242.97	0
188	2	17	30	6.9748	306.43	0
189	1	18	30	6.3109	221.65	0
190	2	18	30	6.1970	276.03	0
191	1	15	31	9.25819999999.00		3
192	2	15	31	9.17359999999.00		3
193	1	16	31	8.58879999999.00		3
194	2	16	31	8.47179999999.00		3
195	1	17	31	7.8882	268.76	0
196	2	17	31	7.7459	327.52	0
197	1	18	31	7.1192	248.45	0
198	2	18	31	6.9908	298.54	0
199	1	16	32	9.32739999999.00		3
200	2	16	32	9.20059999999.00		3
201	1	17	32	8.65259999999.00		3
202	2	17	32	8.49669999999.00		3
203	1	18	32	7.9060	273.39	0
204	2	18	32	7.7637	319.33	0
205	1	17	33	9.39669999999.00		3
206	2	17	33	9.22759999999.00		3
207	1	18	33	8.67209999999.00		3
208	2	18	33	8.51619999999.00		3
209	1	18	34	9.41779999999.00		3
210	2	18	34	9.24869999999.00		3

Network of Possible Solutions in Nodal Form

Note - The criterion function of a node will be very low if all paths leading to it fail to satisfy lead time req. and/or minimum MOE levels.

No.	Sys.	Year	EP	Crit.Fn.	Best.Pred.Node	Best.Pred.Arc	Best.Alt.
1	0	1989	0	0.			
2	1	1989	1	20.000	1	1	0
3	1	1990	2	-27.666	1	2	0
4	1	1991	3	-80.950	1	3	0
5	1	1992	4	-1.000E+007	1	4	0
6	1	1993	5	-1.000E+007	1	5	0
7	1	1994	6	-1.000E+007	1	6	0
8	2	1994	7	-282.339	2	7	1
9	2	1995	9	-395.635	2	10	2
10	2	1996	13	-379.964	4	17	1
11	2	1997	19	-458.632	3	22	2
12	2	1998	27	-498.963	4	32	2
13	2	1999	37	-1.000E+007	2	37	1
14	2	2000	49	-1.000E+007	3	49	1
15	2	2001	59	-1.000E+007	4	59	1
16	2	2002	67	-1.000E+008	0	0	0
17	2	2003	73	-1.000E+008	0	0	0
18	2	2004	77	-1.000E+008	0	0	0
19	3	1999	79	-538.063	8	79	1
20	3	2000	81	-579.163	8	81	1
21	3	2001	85	-617.622	8	85	1
22	3	2002	91	-653.389	8	91	1
23	3	2003	99	-708.410	10	103	1

24	3	2004	109	-741.623	10	113	1
25	3	2005	121	-791.733	11	125	1
26	3	2006	133	-835.932	12	137	1
27	3	2007	145	-1.000E+007	13	149	1
28	3	2008	157	-1.000E+007	12	157	1
29	3	2009	169	-2.000E+007	13	169	1
30	3	2010	181	-1.000E+008	0	0	0
31	3	2011	191	-1.000E+008	0	0	0
32	3	2012	199	-1.000E+008	0	0	0
33	3	2013	205	-1.000E+008	0	0	0
34	3	2014	209	-1.000E+008	0	0	0

Minimum Average Annual Cost Solution Path
(Time value of money is ignored, ie. interest rate is assumed to be 0)

Node	Transition Year	System	Alternative Employed	Life-Cycle Cost	Life-Cycle Effectiveness	Criterion Func.Value
24	2004	3	1	361.659	7.427	-741.623
10	1996	2	1	299.014	4.808	-379.964
4	1991	1	0	80.950	2.263	-80.950

Minimum Annualised Cost Solution Path
(Monetary interest assumed constant at 5.000 % per annum)

Node	Transition Year	System	Alternative Employed	Life-Cycle Cost	Life-Cycle Effectiveness	Criterion Func.Value
22	2002	3	1	371.050	7.257	-653.389
8	1994	2	1	302.339	4.702	-282.339
2	1989	1	0	-20.000	.775	20.000

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